

Measurements of Field Quality in Helical Dipoles for RHIC

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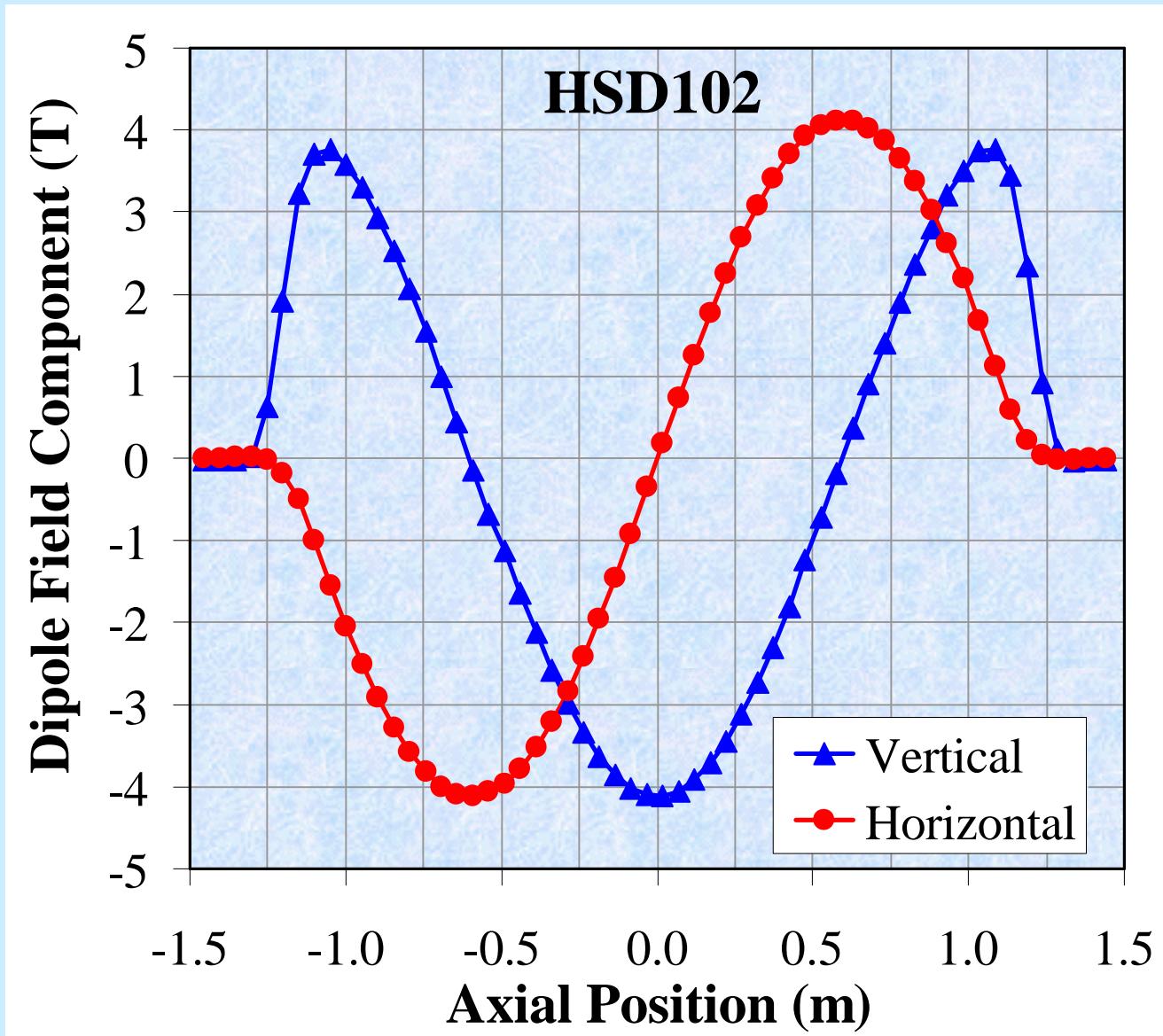
Introduction

- BNL is producing helical dipoles for Siberian Snakes and Spin Rotators to be installed in RHIC under a joint BNL-RIKEN spin physics program.
- The dipole field in these magnets rotates by 360 degrees over a length of 2.4 meters. This feature makes the measurements of these magnets more difficult than usual accelerator magnets with essentially a 2-D field over most of the length.

Picture of a helical dipole magnet coil



Axial Variation of Dipole Field Components



Harmonic Expansion

- Axial variation results in a 3-D field.
- A simple harmonic expansion results under the assumption of periodicity along the Z-axis with wavelength \mathbf{l} :

$$B_{r,\mathbf{q},z}(r,\mathbf{q},z) \equiv B_{r,\tilde{\mathbf{q}},z}(r,\tilde{\mathbf{q}}); \quad \tilde{\mathbf{q}} = \mathbf{q} - kz$$

$$k = (d\mathbf{a}/dz) = \text{rate of change of dipole field angle} = 2\mathbf{p}/\mathbf{l}$$

$$B_r(r,\tilde{\mathbf{q}}) = B_0 \sum_{n=1}^{\infty} \left[\frac{2^n n!}{n^n (kR_{ref})^{n-1}} \right] I'_n(nkr) [\tilde{b}_n \sin(n\tilde{\mathbf{q}}) + \tilde{a}_n \cos(n\tilde{\mathbf{q}})]$$

$$B_{\mathbf{q}}(r,\tilde{\mathbf{q}}) = B_0 \sum_{n=1}^{\infty} \left[\frac{2^n n!}{n^n (kR_{ref})^{n-1}} \right] \frac{I_n(nkr)}{kr} [\tilde{b}_n \cos(n\tilde{\mathbf{q}}) - \tilde{a}_n \sin(n\tilde{\mathbf{q}})]$$

$$B_z(r,\tilde{\mathbf{q}}) = -(kr)B_{\mathbf{q}}(r,\tilde{\mathbf{q}}) \quad n = 1 \text{ is Dipole term, etc.}$$

Harmonic Expansion

- \tilde{b}_n and \tilde{a}_n are ideally constants, representing the normal and the skew components in a reference frame that rotates along the magnet length.
- In a reference frame fixed in space, the normal and the skew coefficients are functions of the axial position:

$$b_n(z) = \tilde{b}_n \cos(nkz) + \tilde{a}_n \sin(nkz)$$

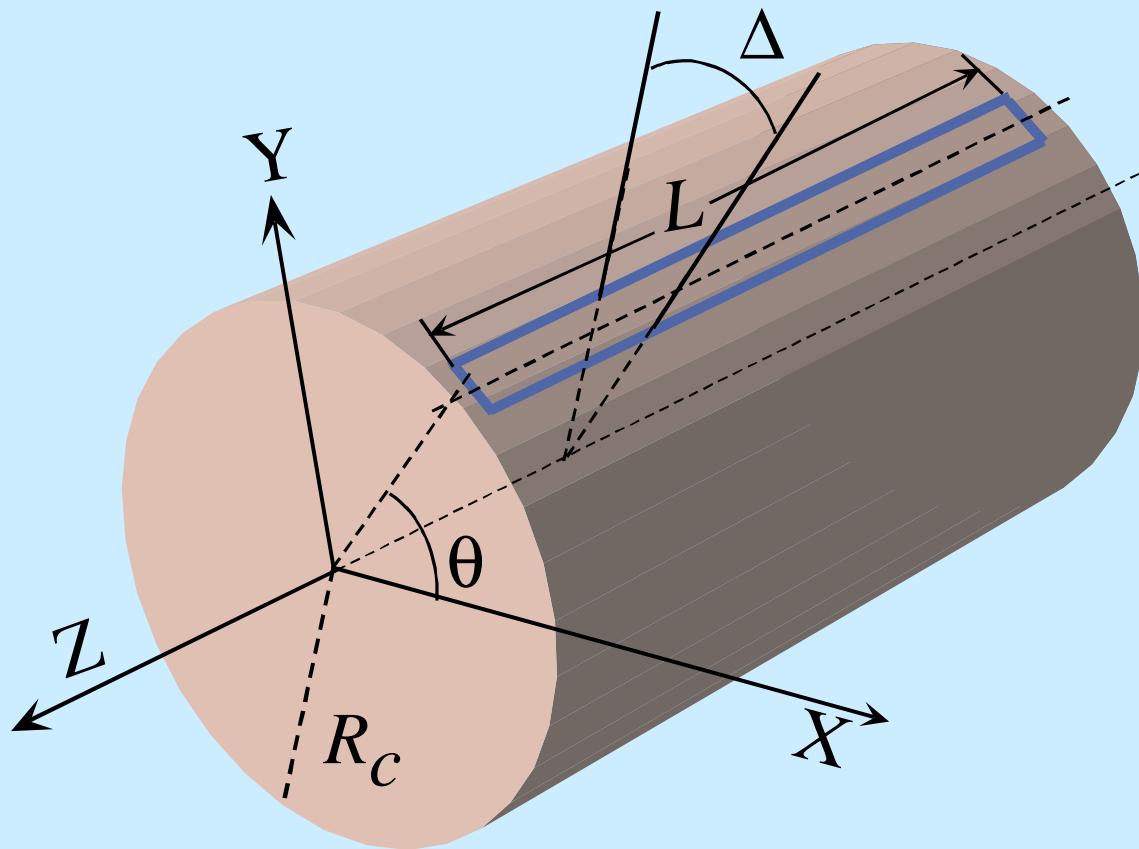
$$a_n(z) = \tilde{a}_n \cos(nkz) - \tilde{b}_n \sin(nkz)$$

- All harmonics oscillate with axial position; the higher harmonics do so more rapidly.
- This implies that if a conventional rotating coil is employed to measure the harmonics, the coil must be as short as possible to avoid cancellation of signal over its length.

Measuring Coil Parameters

- 34.2 mm radius (Reference radius for these magnets is 31 mm)
- Only 51 mm long, less than one diameter, and about 2% of the wavelength.
- Tangential winding: 56 turns, 15.4 degrees.
- Two Dipole Buck windings: 6 turns each.
- The no. of turns is about twice the typical RHIC coils, to compensate for lower signal due to the short length.
- Has two quadrupole buck windings also, but these are not used for the dipole tests.

Flux through a Tangential Coil



$$\Phi(\mathbf{q}, z) = N \int_{\mathbf{q}-\Delta/2}^{\mathbf{q}+\Delta/2} \int_{z-L/2}^{z+L/2} \mathbf{B}_r(R_c, \mathbf{q}, z) \cdot \mathbf{R}_c \, dz \, d\mathbf{q}$$

Flux through a Tangential Coil

$$\Phi(\mathbf{q}, z) = \sum_{n=1}^{\infty} \mathfrak{R}_n(R_c) \left[\frac{2NLR_c}{n} \right] \sin\left(\frac{n\Delta}{2}\right)$$

$$\times \left[\frac{\sin(nkL/2)}{nkL/2} \right]$$

$$\times [A_n(z)\cos(n\mathbf{q}) + B_n(z)\sin(n\mathbf{q})]$$

where \tilde{A}_n and \tilde{B}_n are assumed constants over the coil length, and

$$\mathfrak{R}_n(r) = \left[\frac{2^n n!}{n^n (kR_{ref})^{n-1}} \right] I'_n(nkr)$$

$\mathfrak{R}_n(r)$ differs from $(r/R_{ref})^{n-1}$ by 0.25% for the dipole term and by 2.7% for the 30 - pole term for $r = R_{ref} = 31$ mm.

The voltage signals can be computed from the above expression for the flux. These expressions are used to analyze the data.

Results

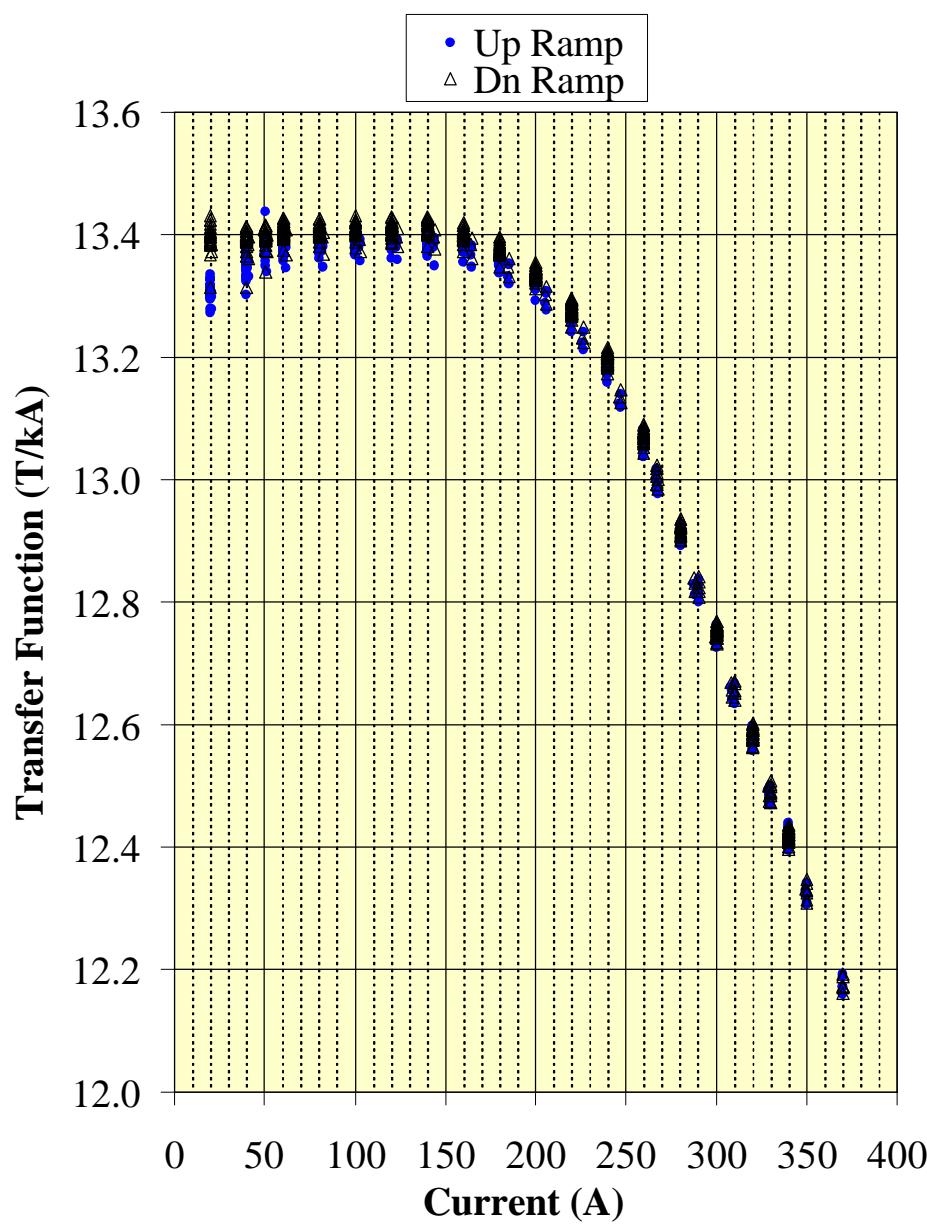
- Measurements as a function of current at a single location in the center of the magnet .
[Gives saturation behaviour of various harmonics.]
- Measurements as a function of axial position at several currents (Z-scans, typically at 102 A, 267 A and 329 A)
[Gives uniformity of field quality over the magnet length, as well as harmonics in the ends.]

It should be noted that the data analysis requires knowledge of the twist pitch, k . The design value of 2.618 m^{-1} corresponding to $\lambda = 2.4 \text{ m}$ is used. The analysis is not strictly valid in the ends, but the error is expected to be only a few percent for the harmonics of interest, and is neglected.

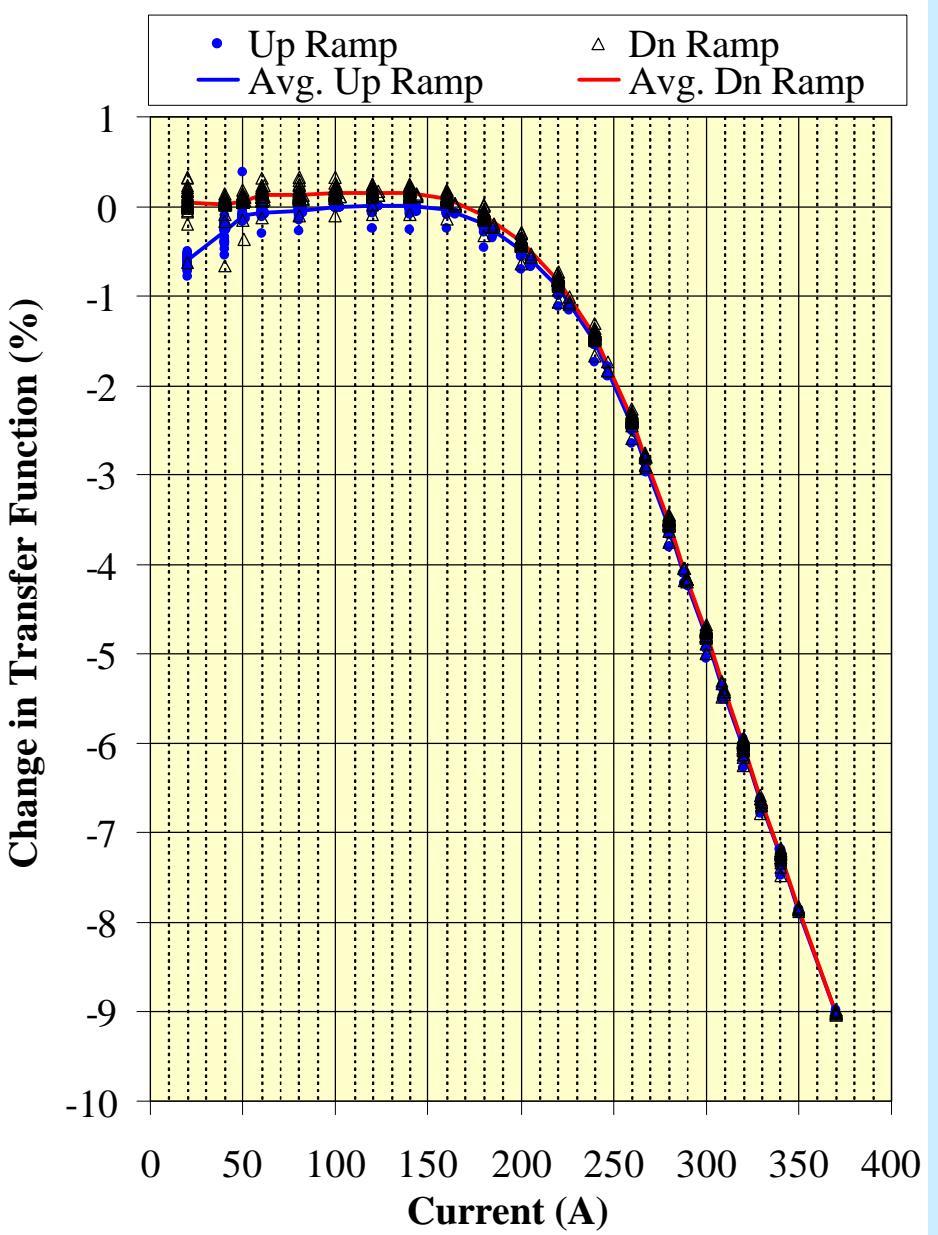
Variation of harmonics with current

- There is considerable magnet to magnet variation in the geometric harmonics. This makes it difficult to compare the saturation behaviour of different magnets in a plot of raw data.
- There are several types of dipoles – with left handed and right handed rotations, and with the dipole field either vertical or horizontal at the center position.
- To compare all the magnets in a single plot, the harmonics are expressed in a coordinate system where the Y-axis coincides with the dipole field
- Two plots for each harmonic are presented here. An “unshifted” plot shows the raw data, indicating the range of geometric values. A “shifted” plot shows the same data after the value at 102 A (up ramp) is subtracted out to eliminate geometric differences between different magnets.

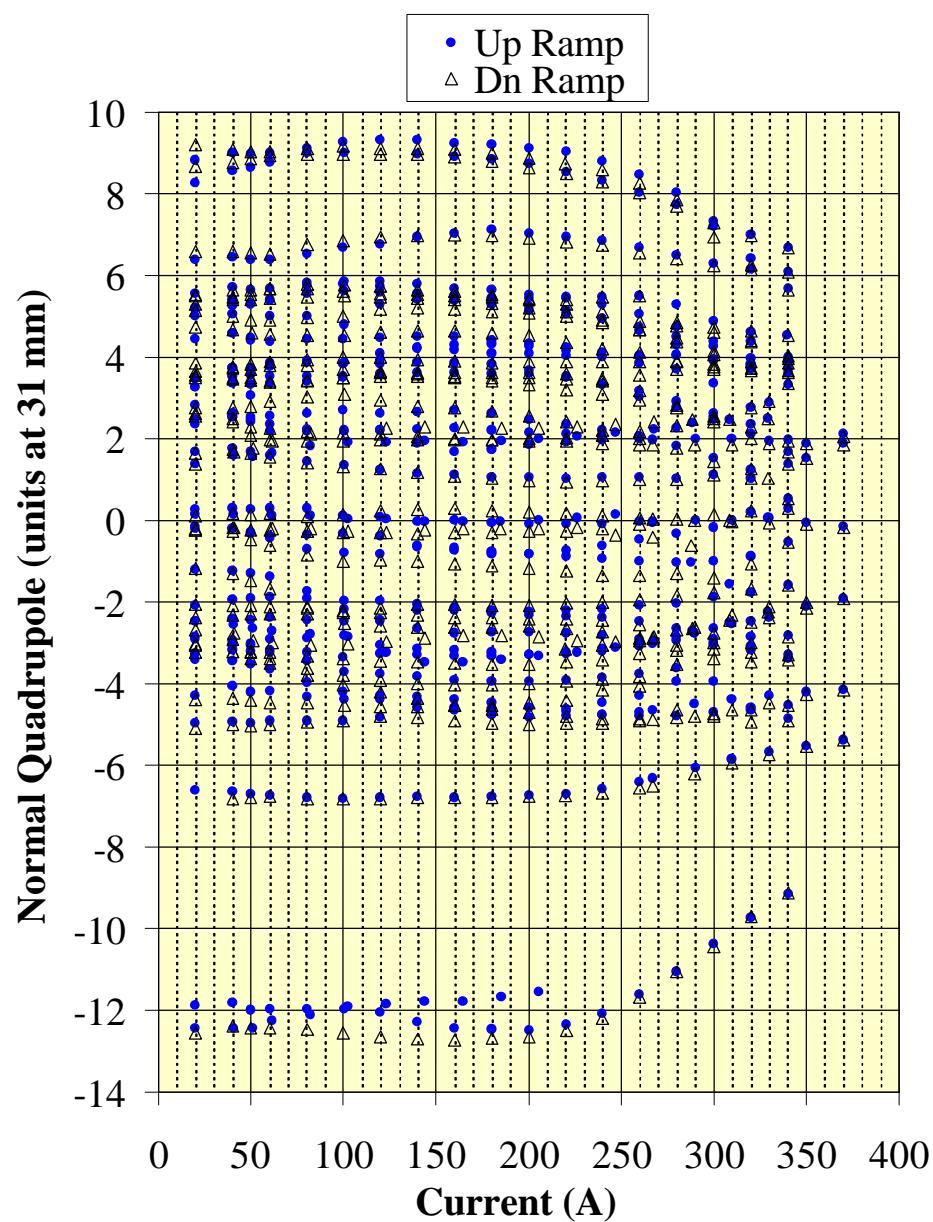
HSD Dipoles: Center; Unshifted Data



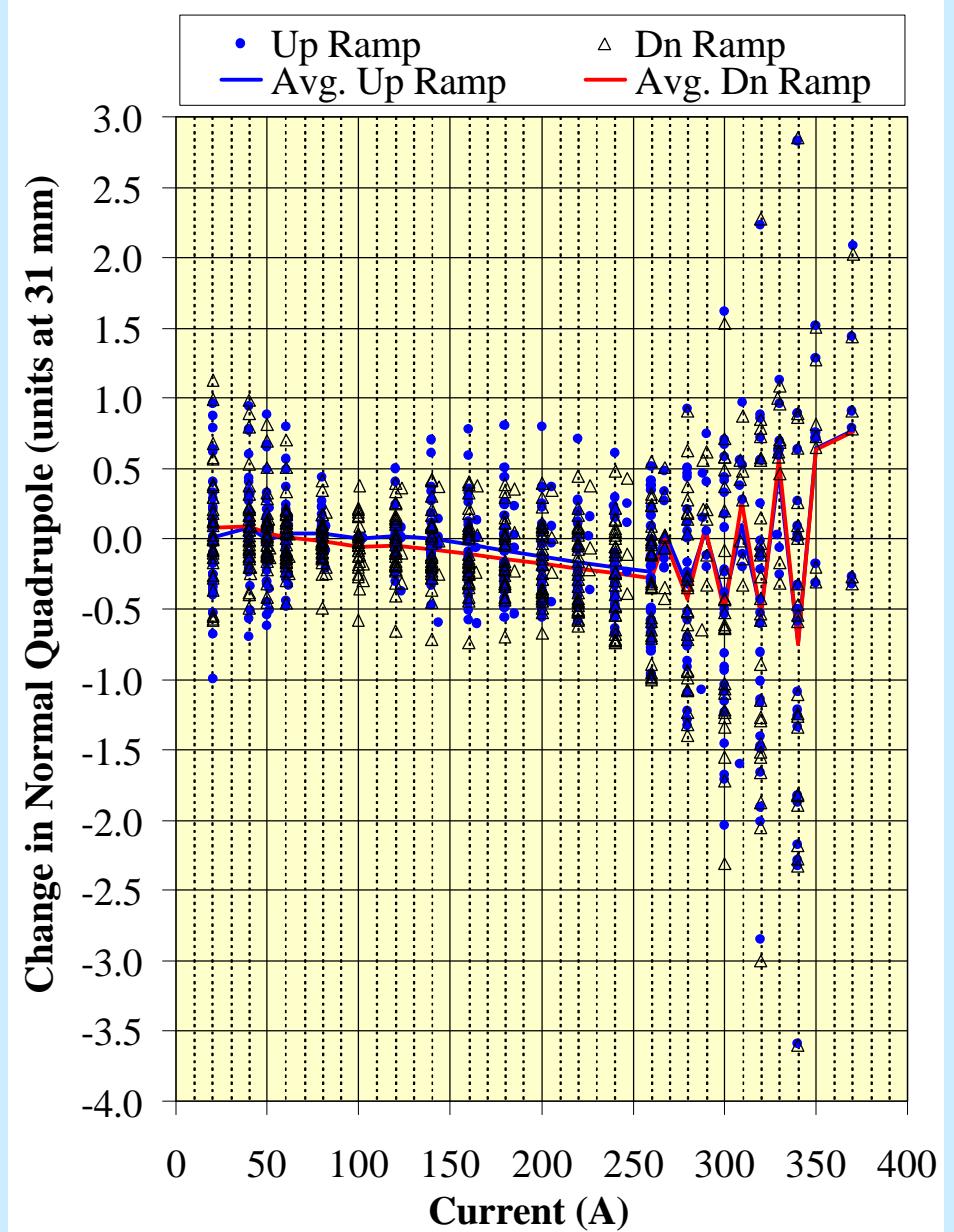
HSD Dipoles: Center; Shifted Data



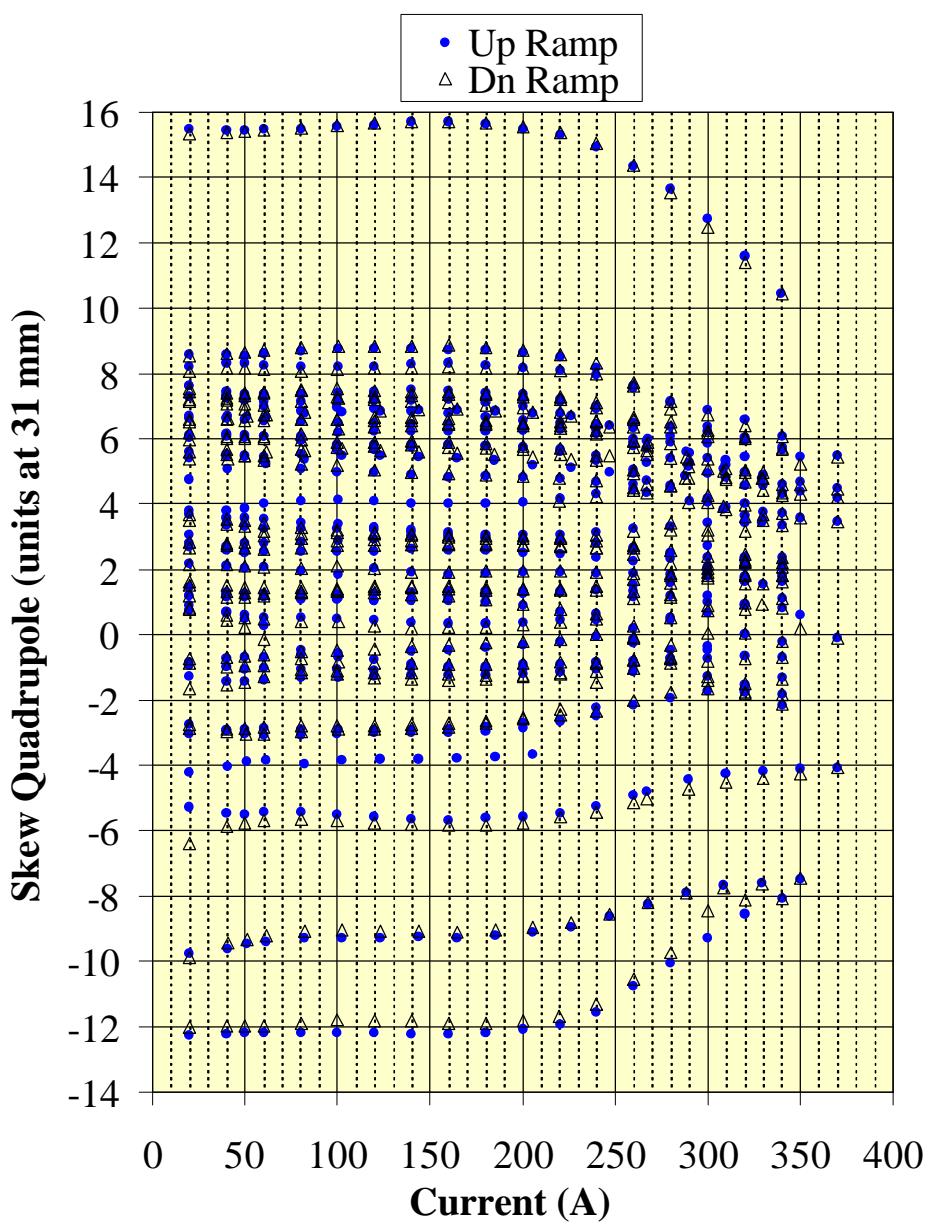
HSD Dipoles: Center; Unshifted Data



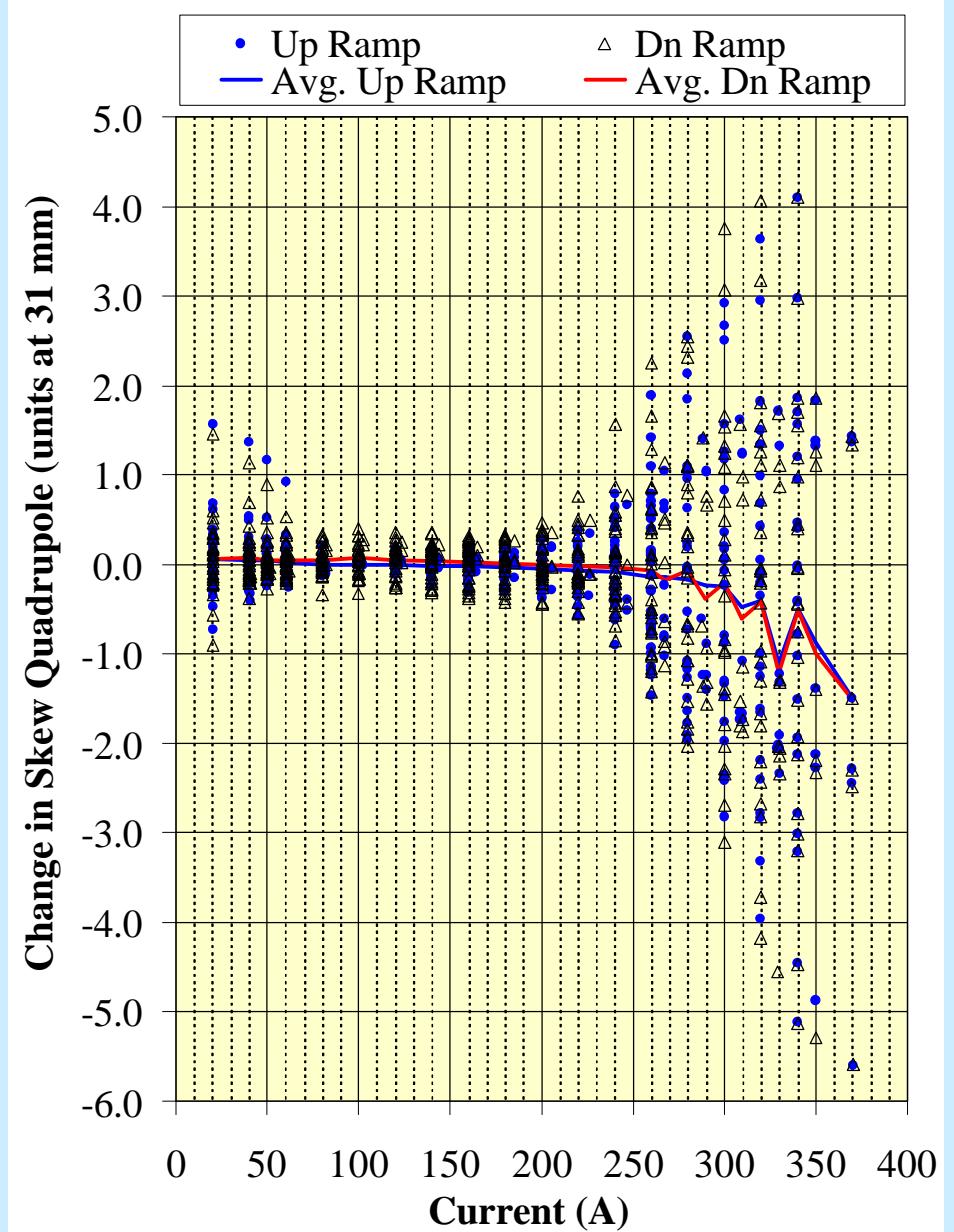
HSD Dipoles: Center; Shifted Data



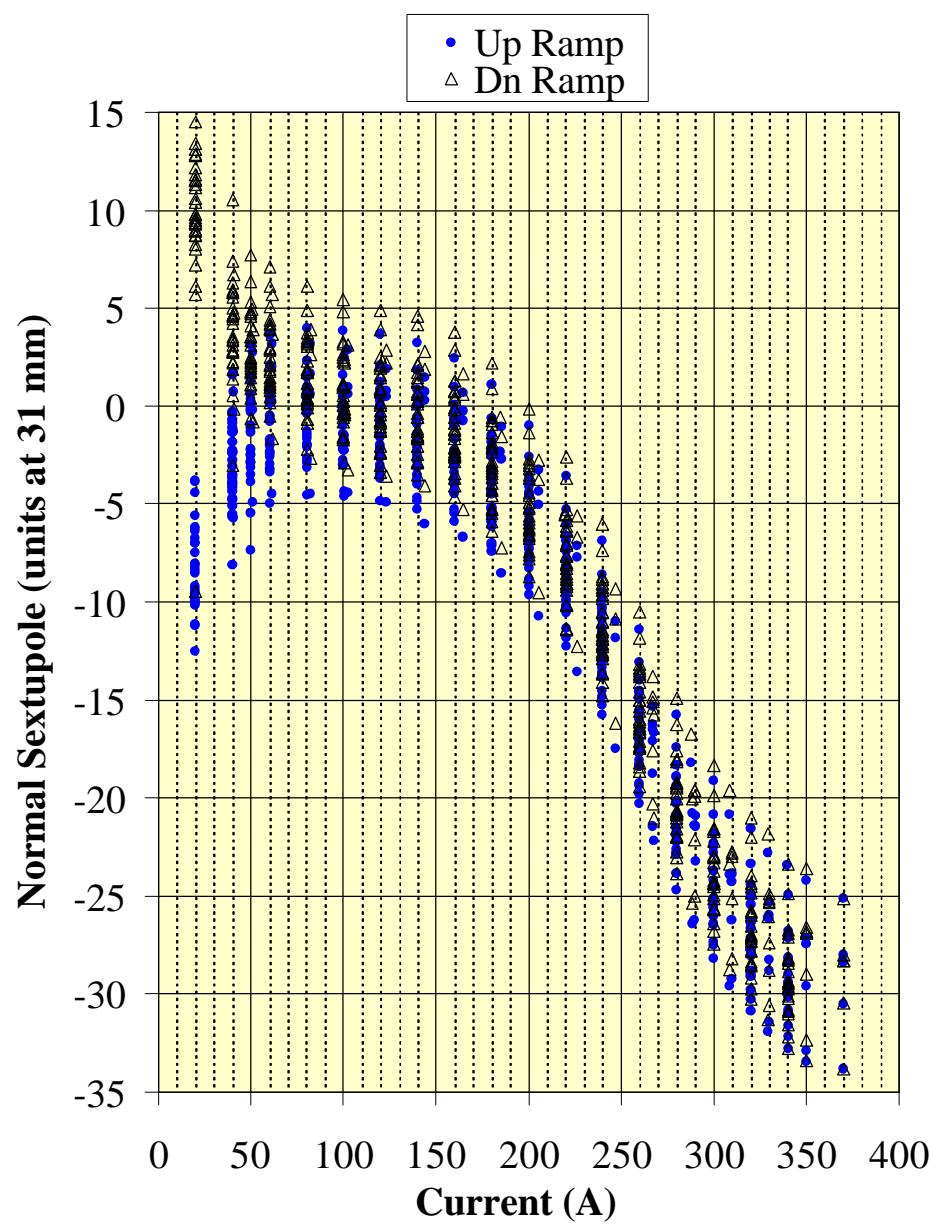
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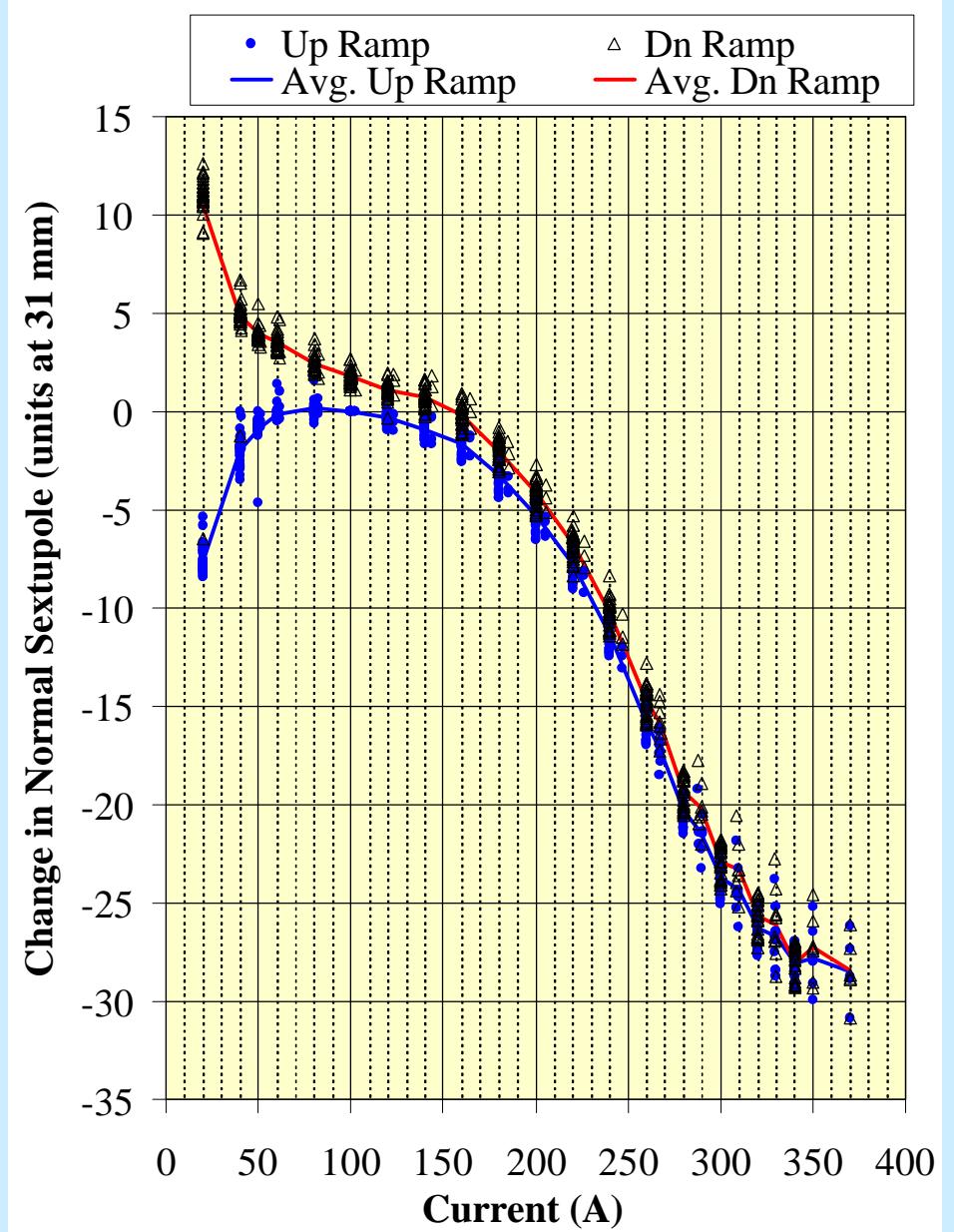
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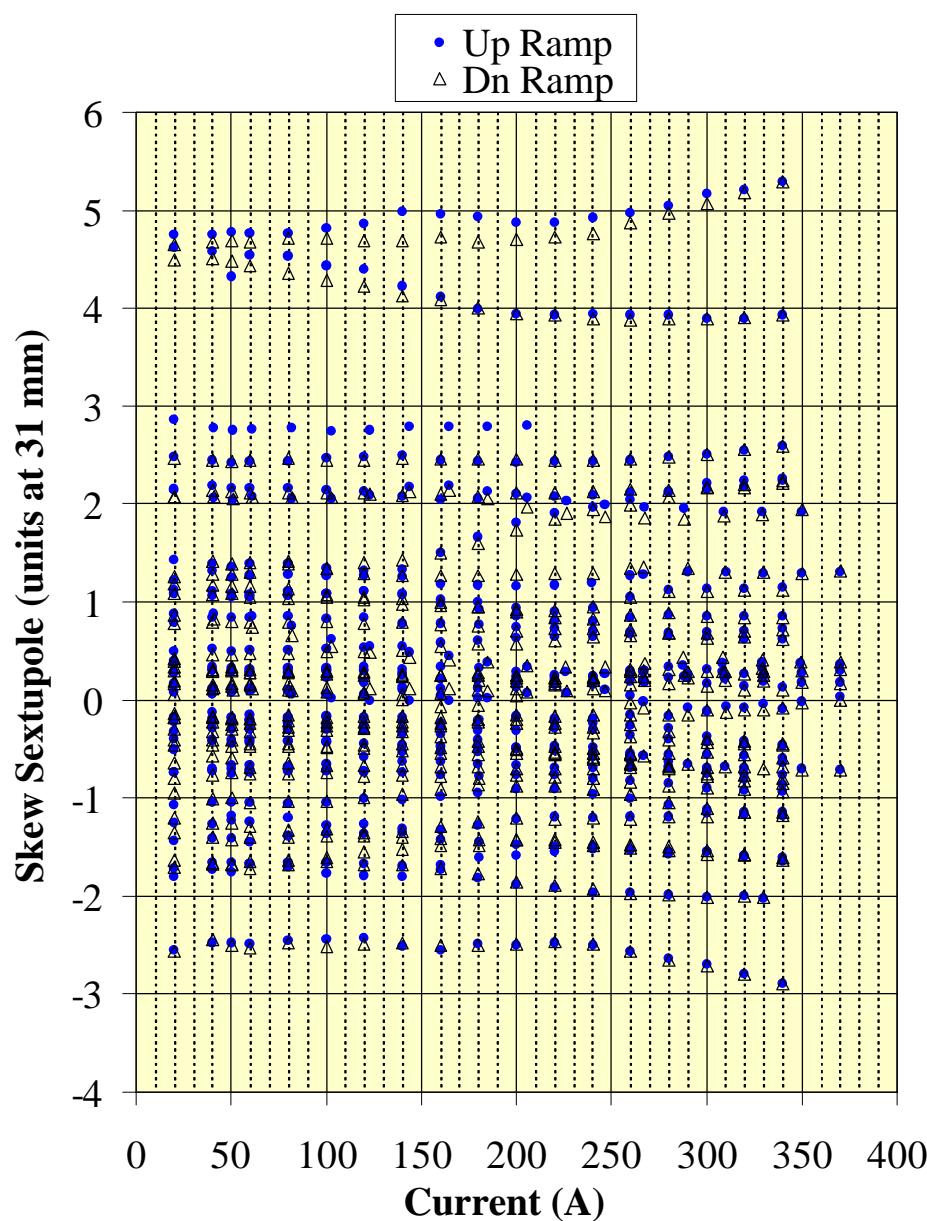
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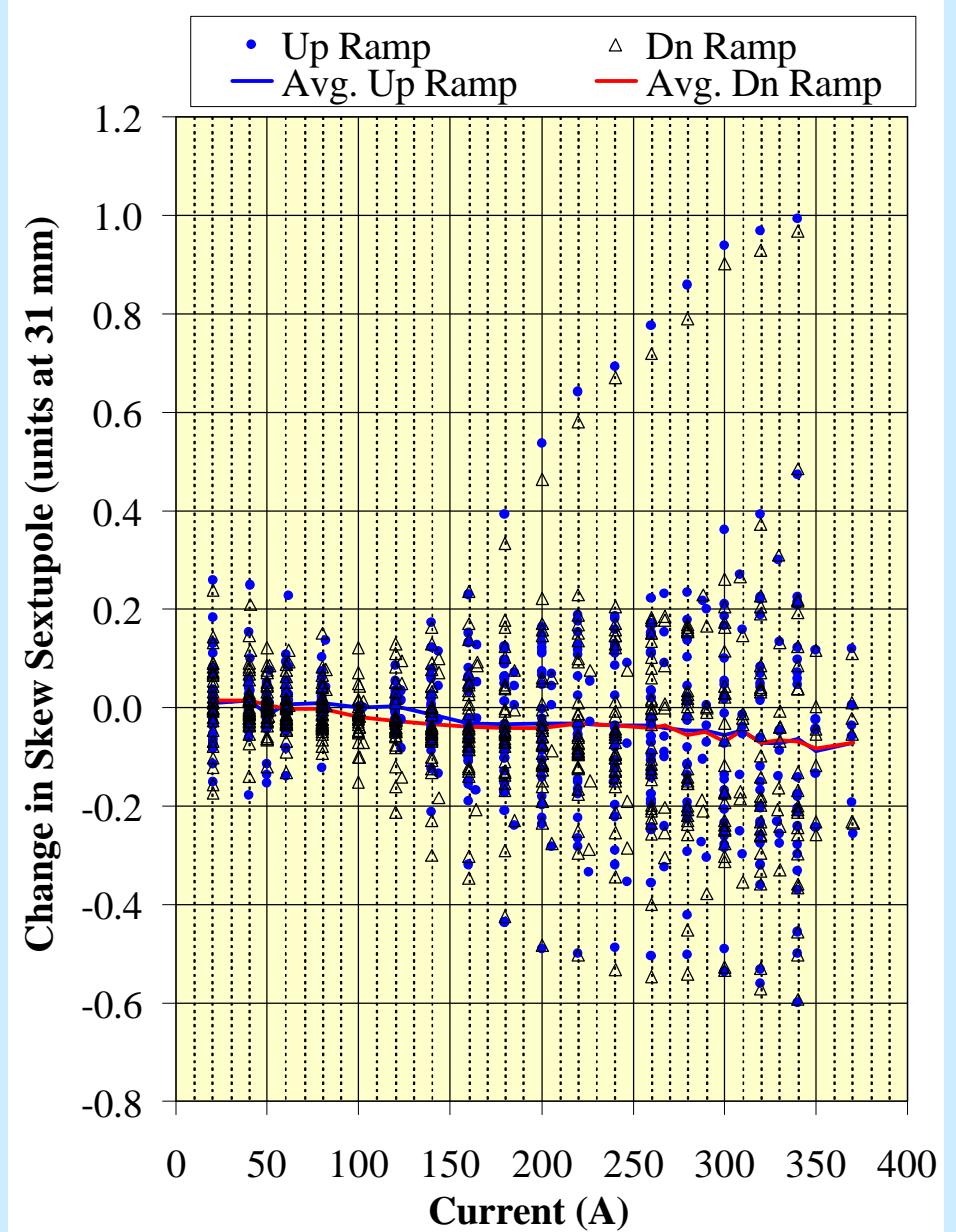
HSD Dipoles: Center; Shifted Data



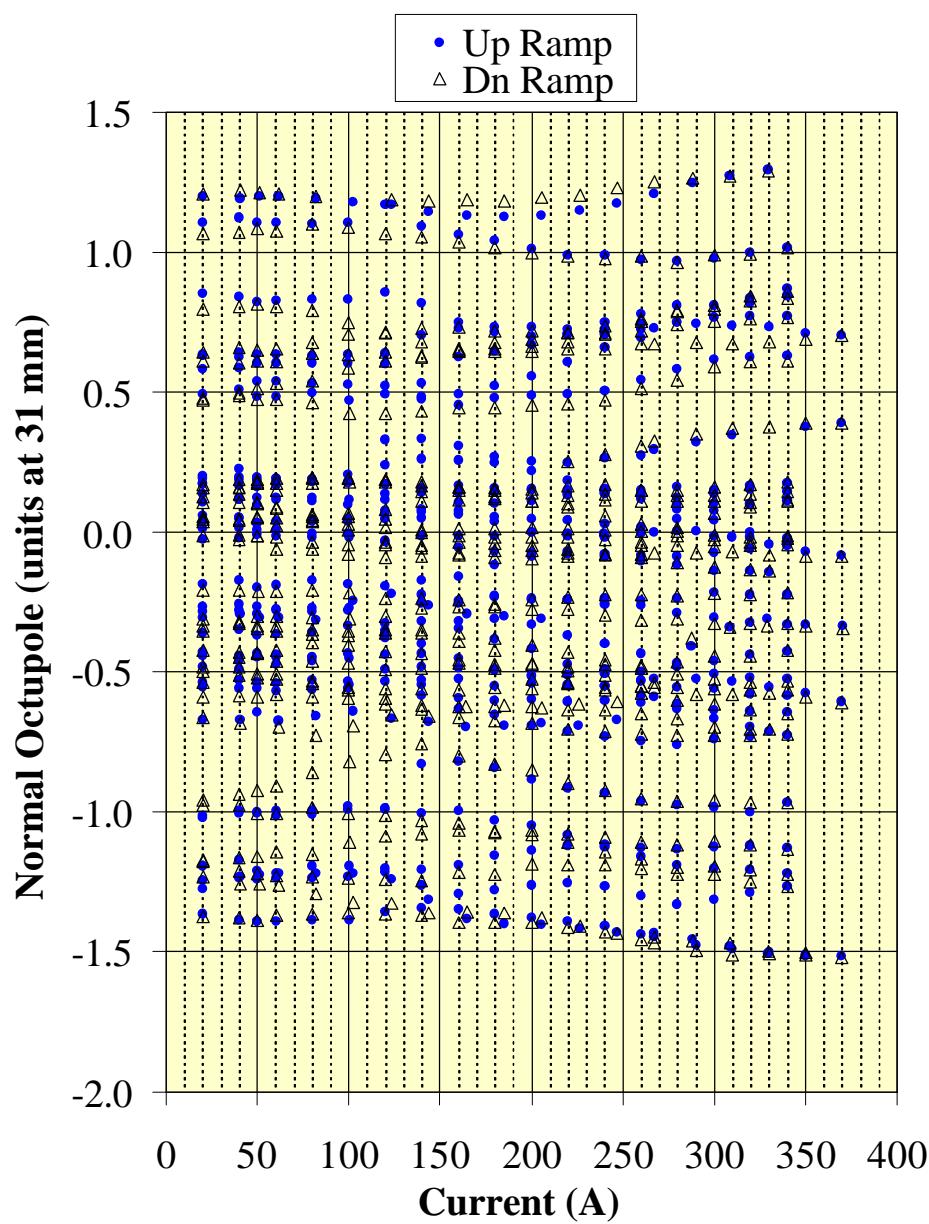
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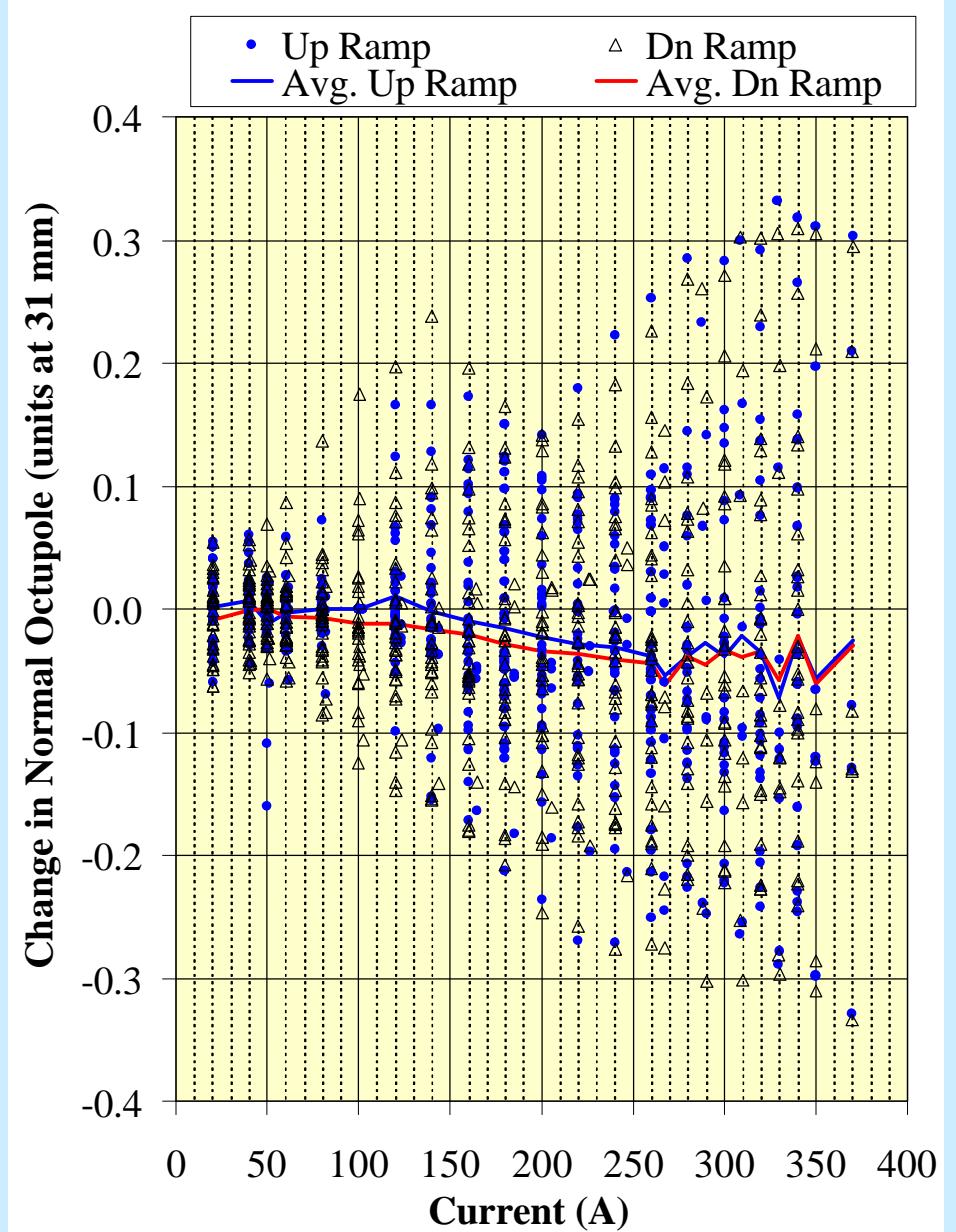
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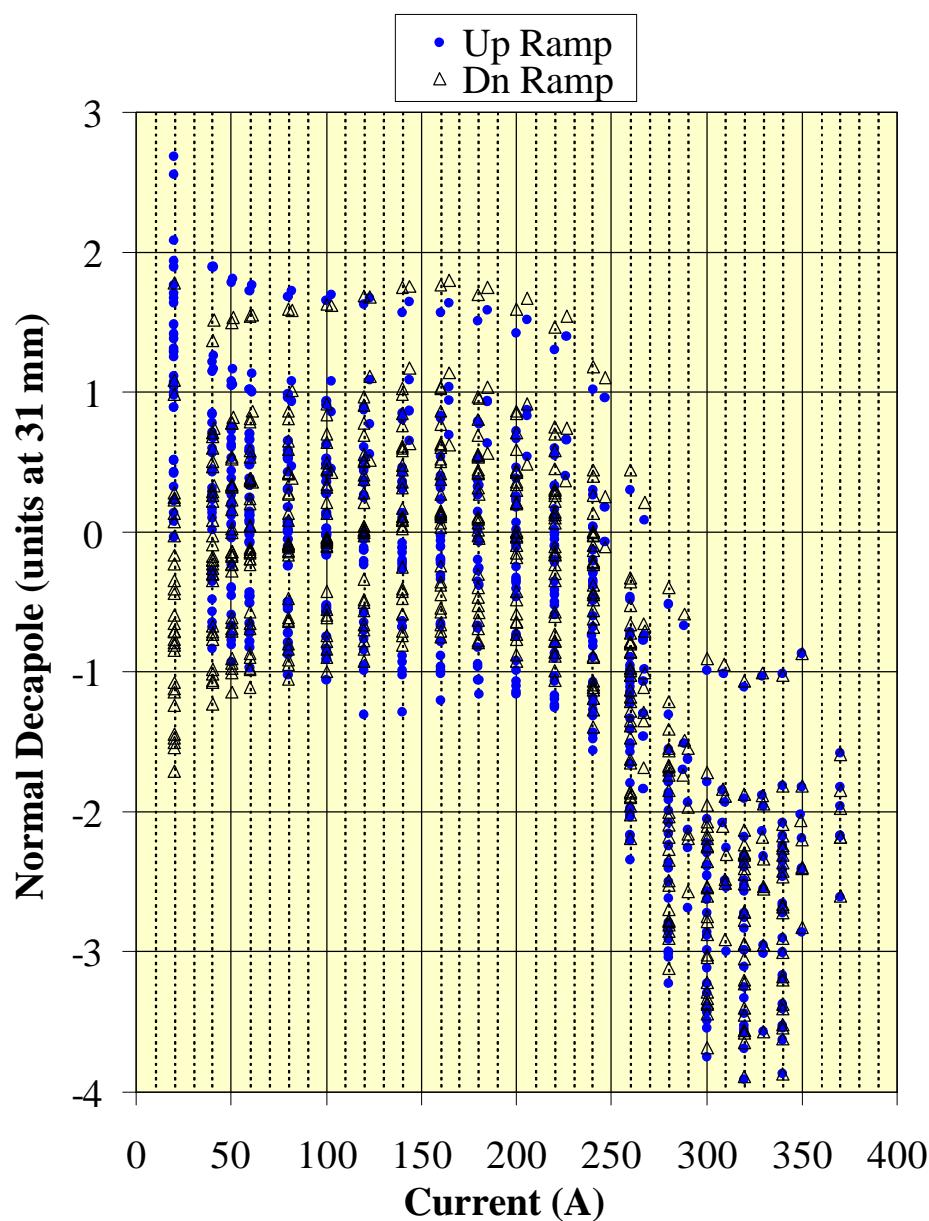
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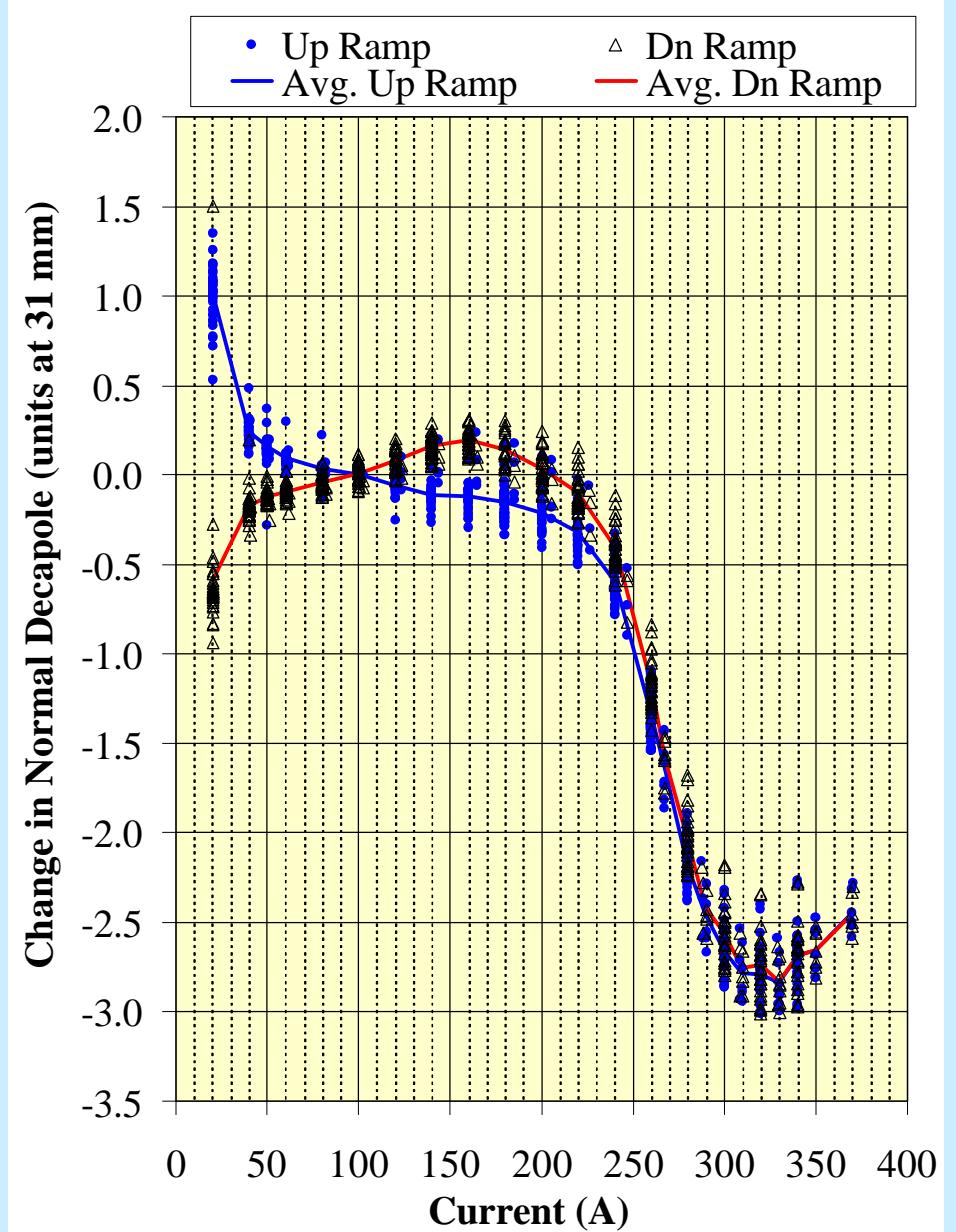
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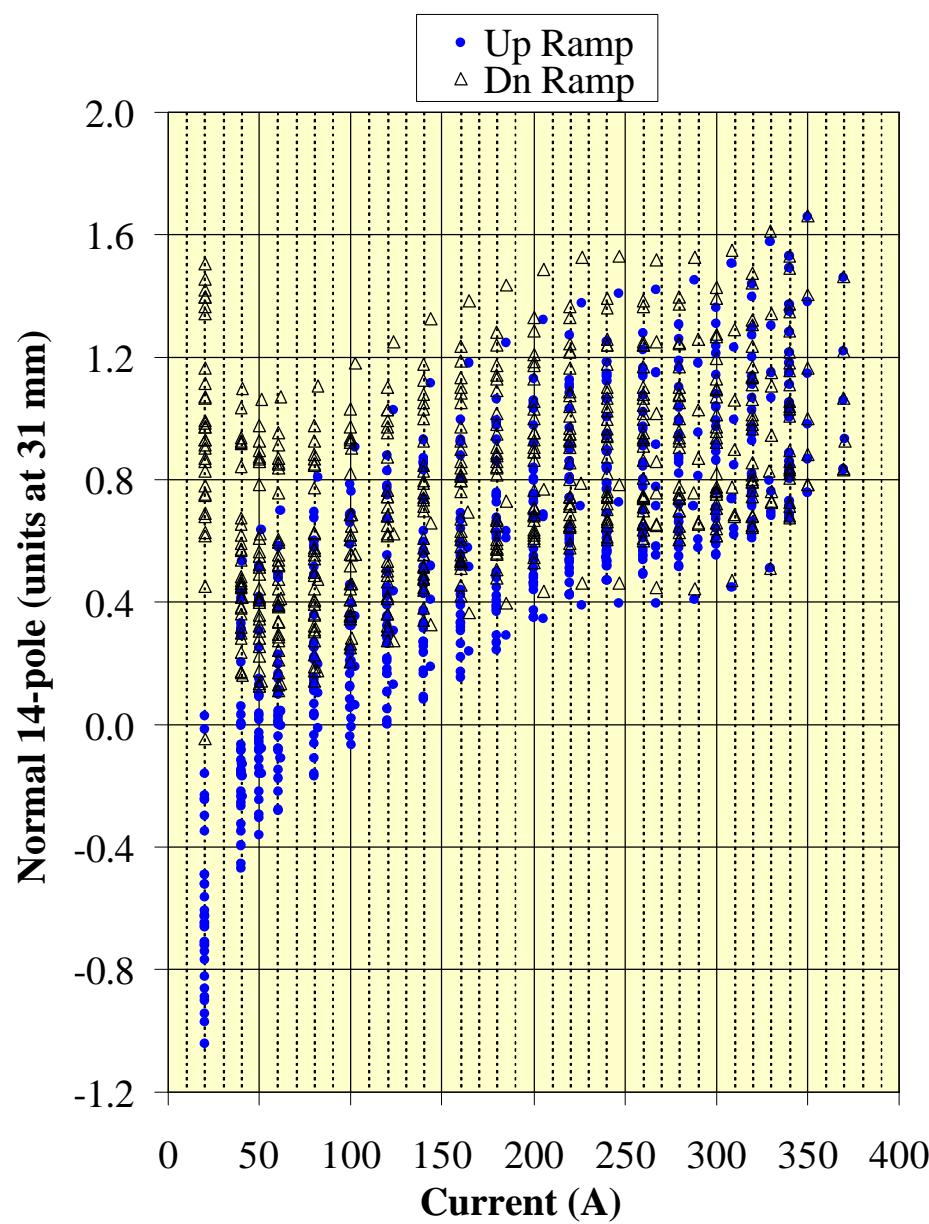
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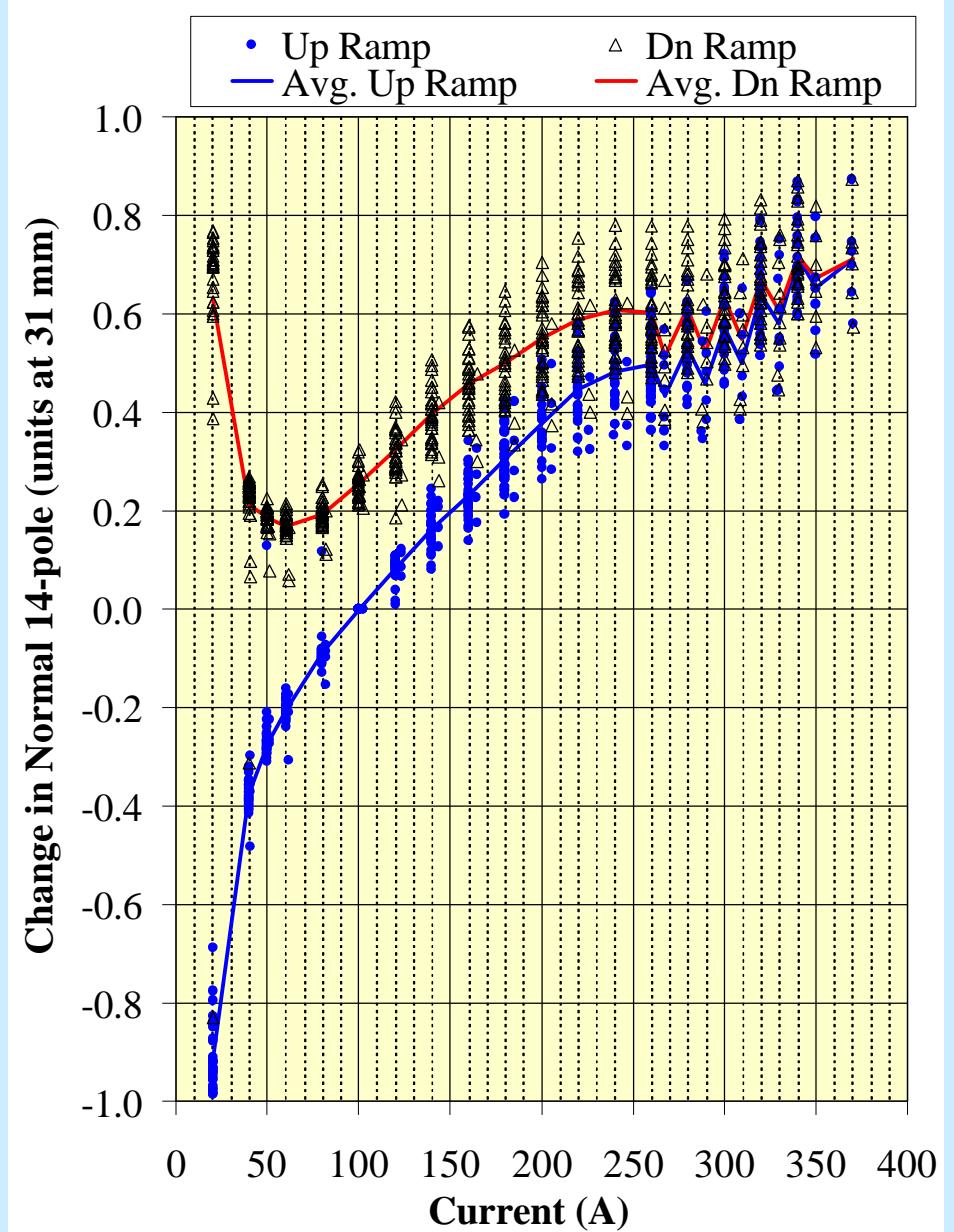
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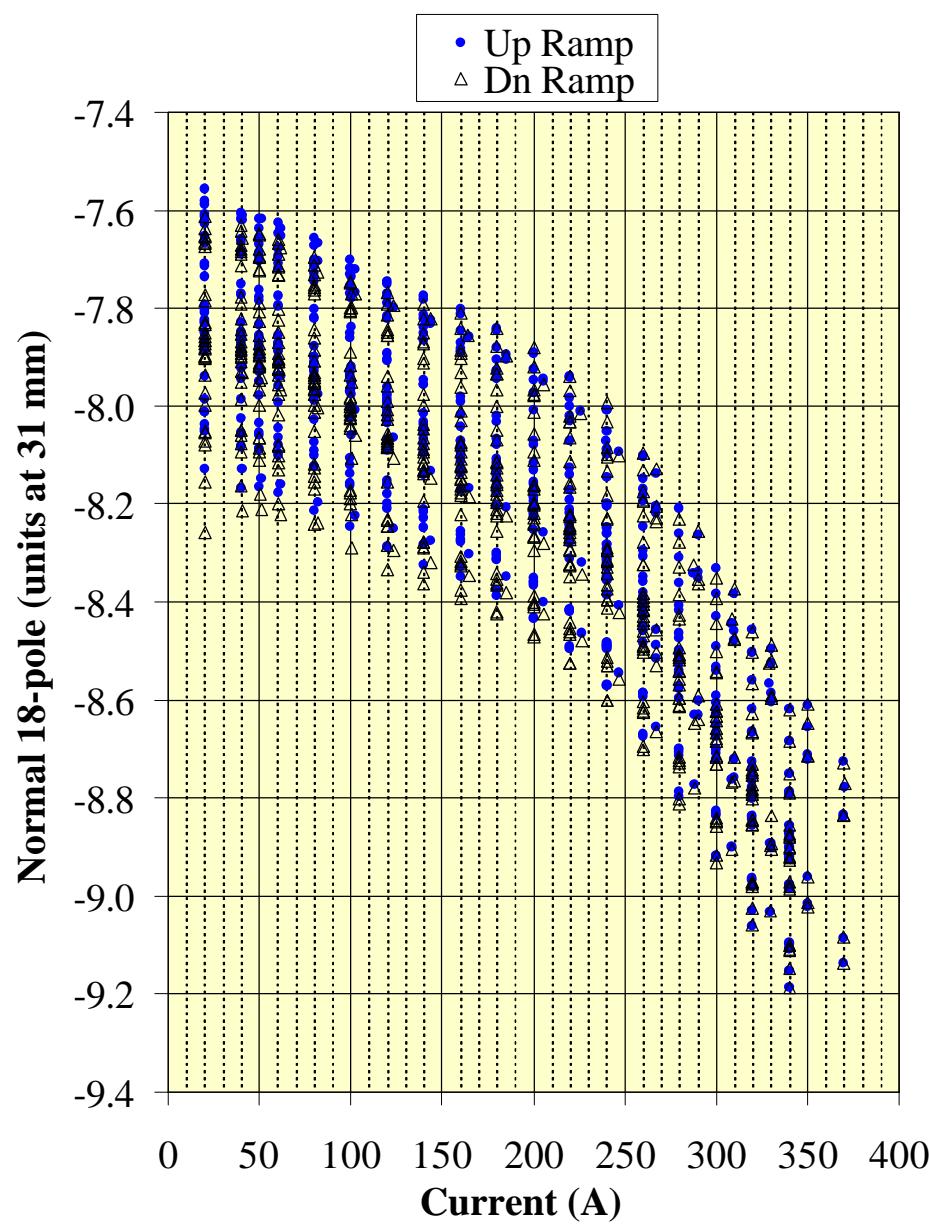
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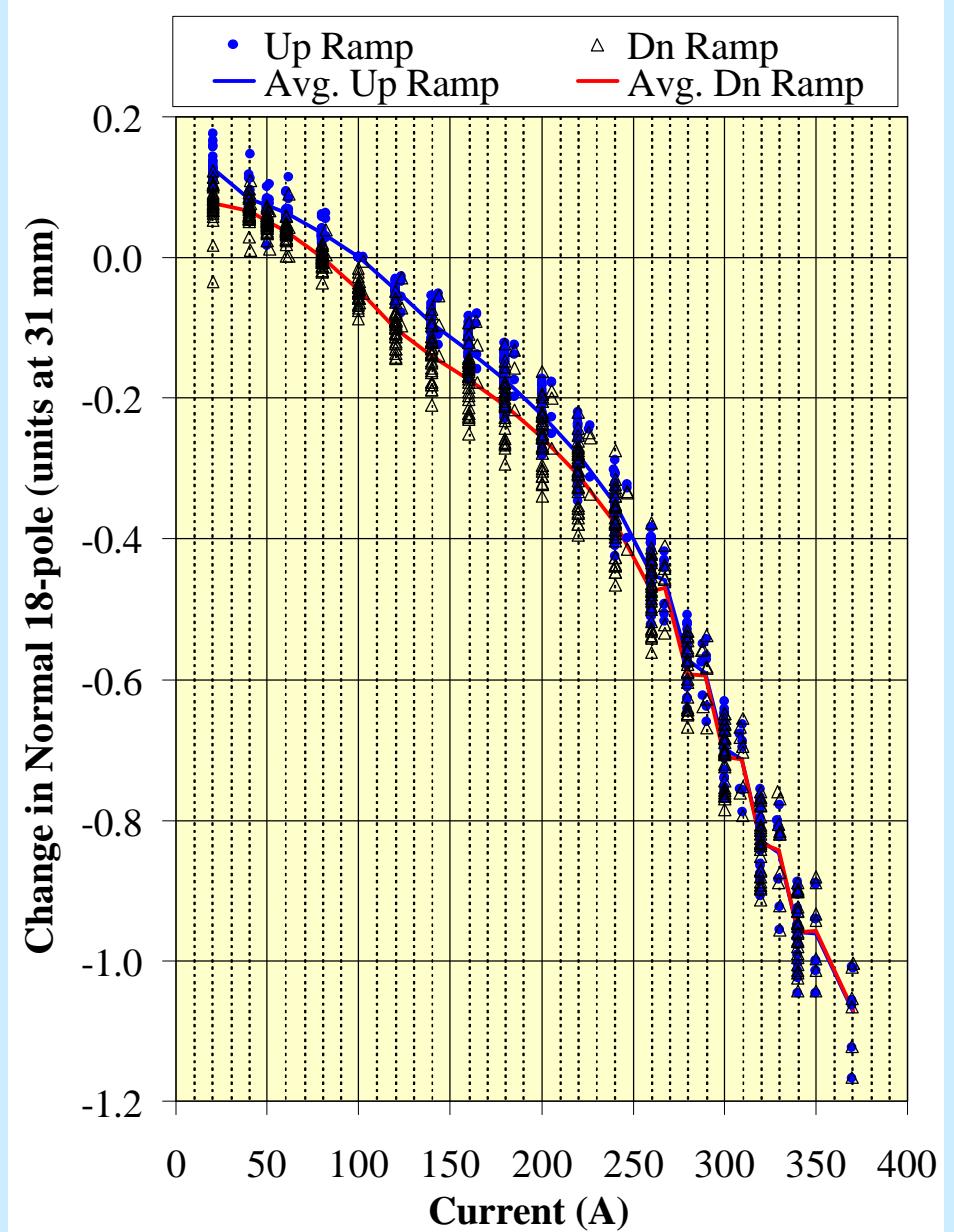
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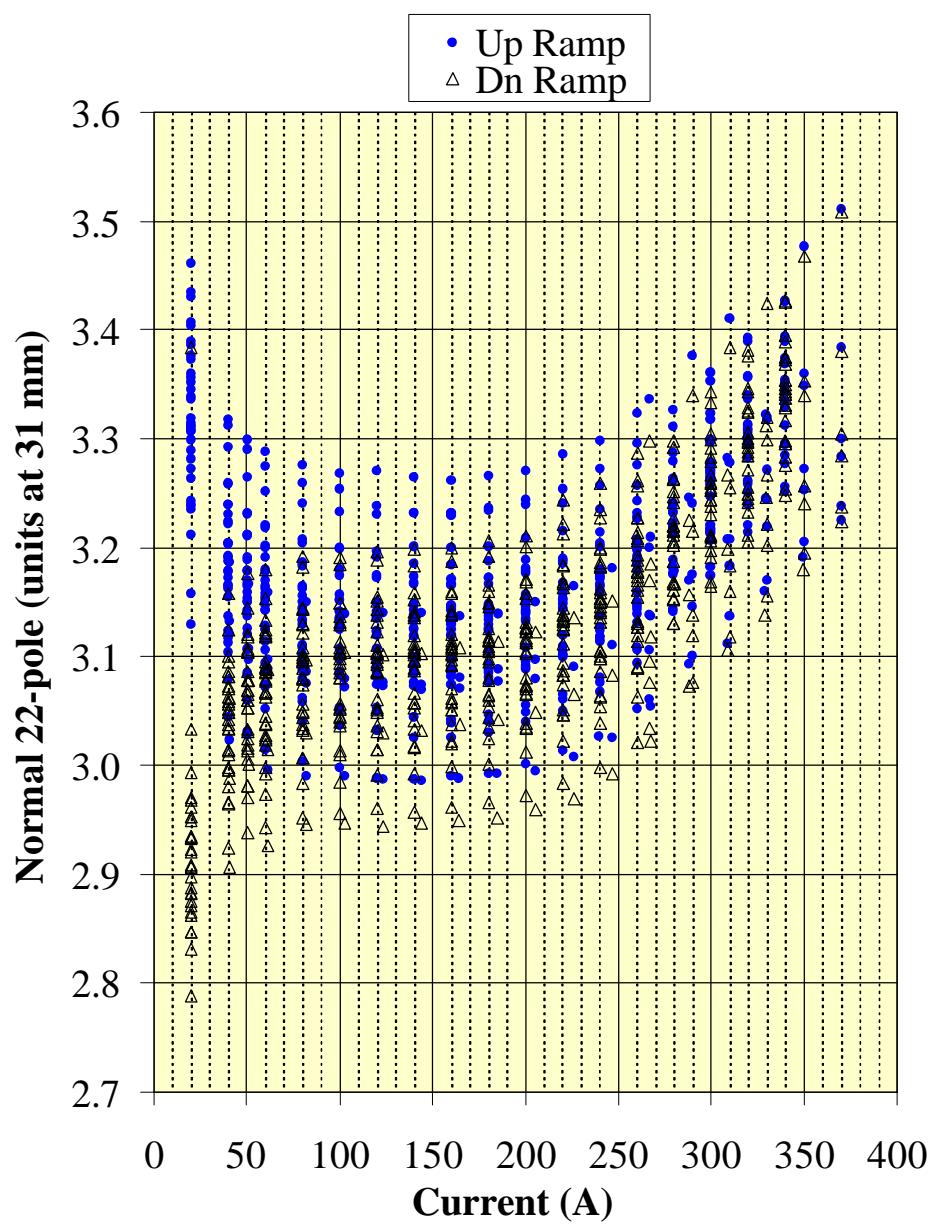
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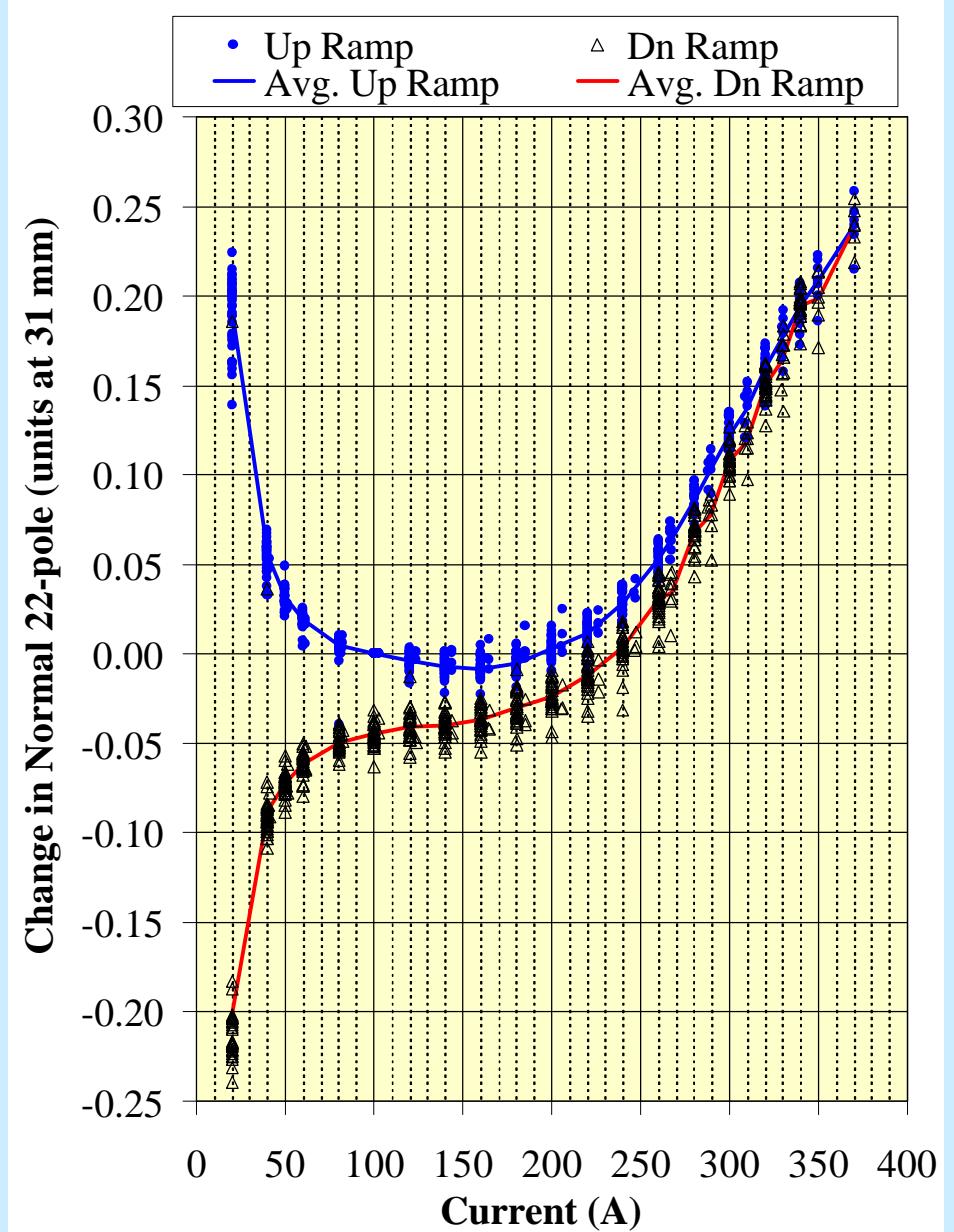
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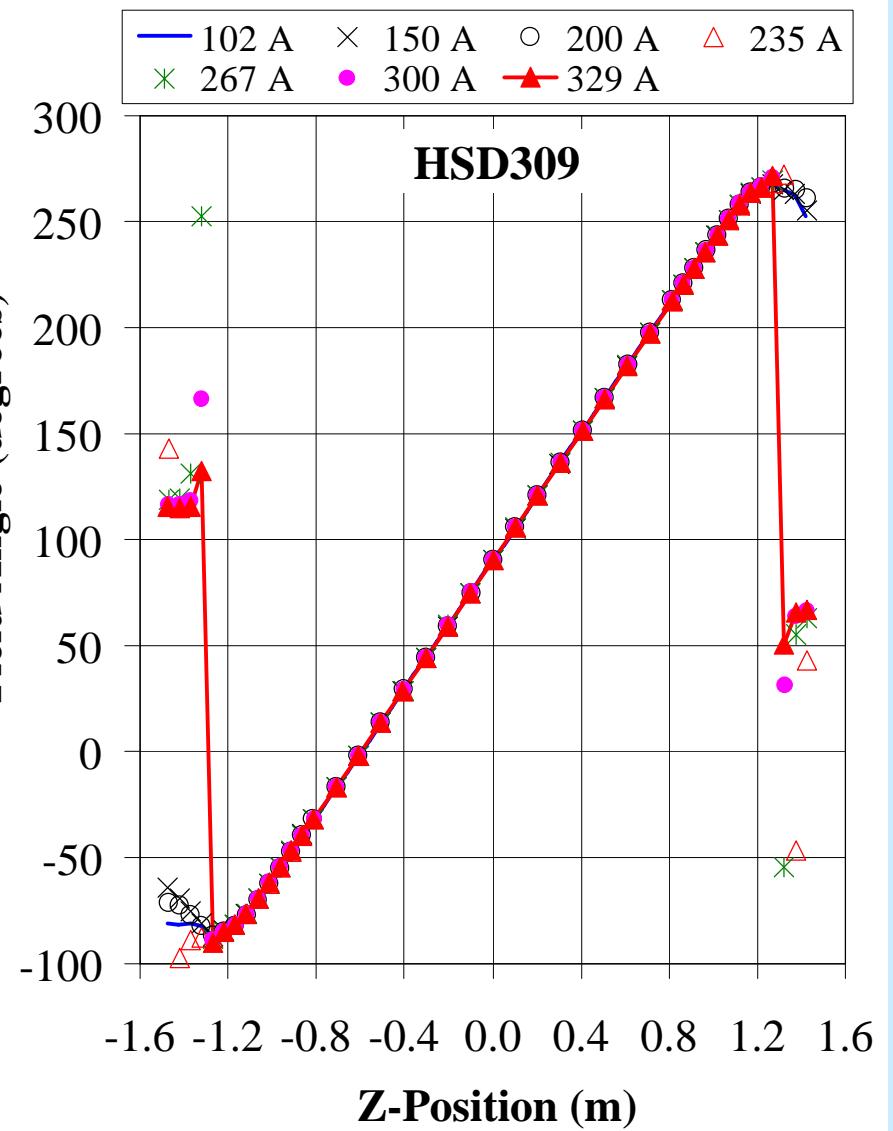
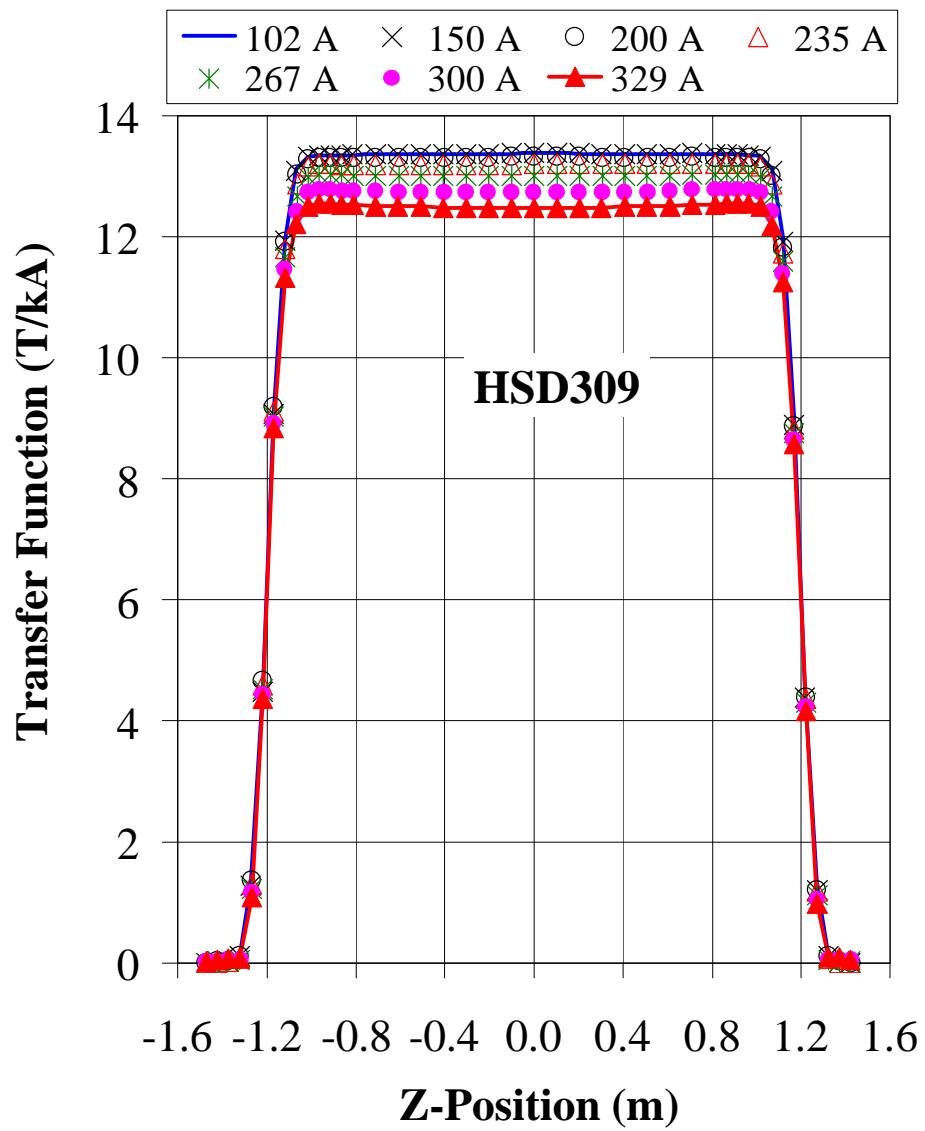
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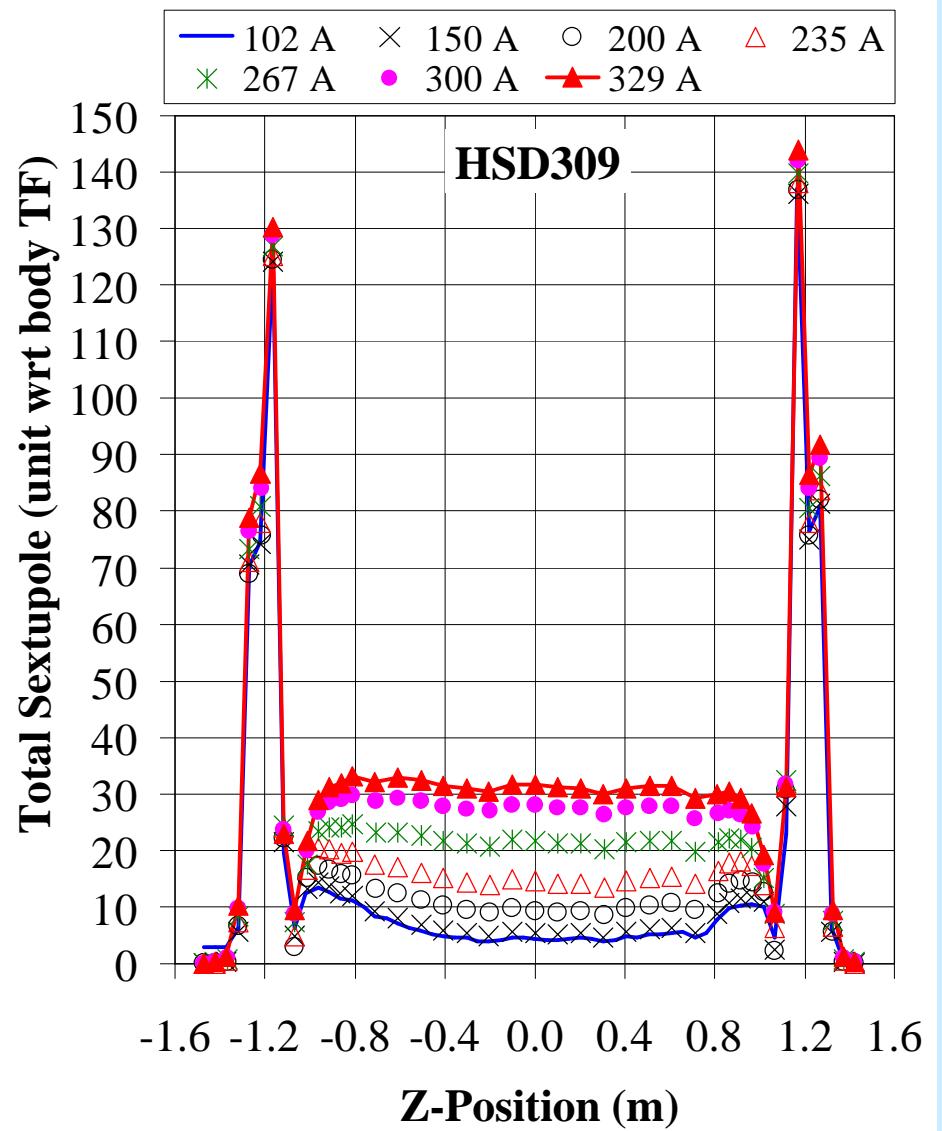
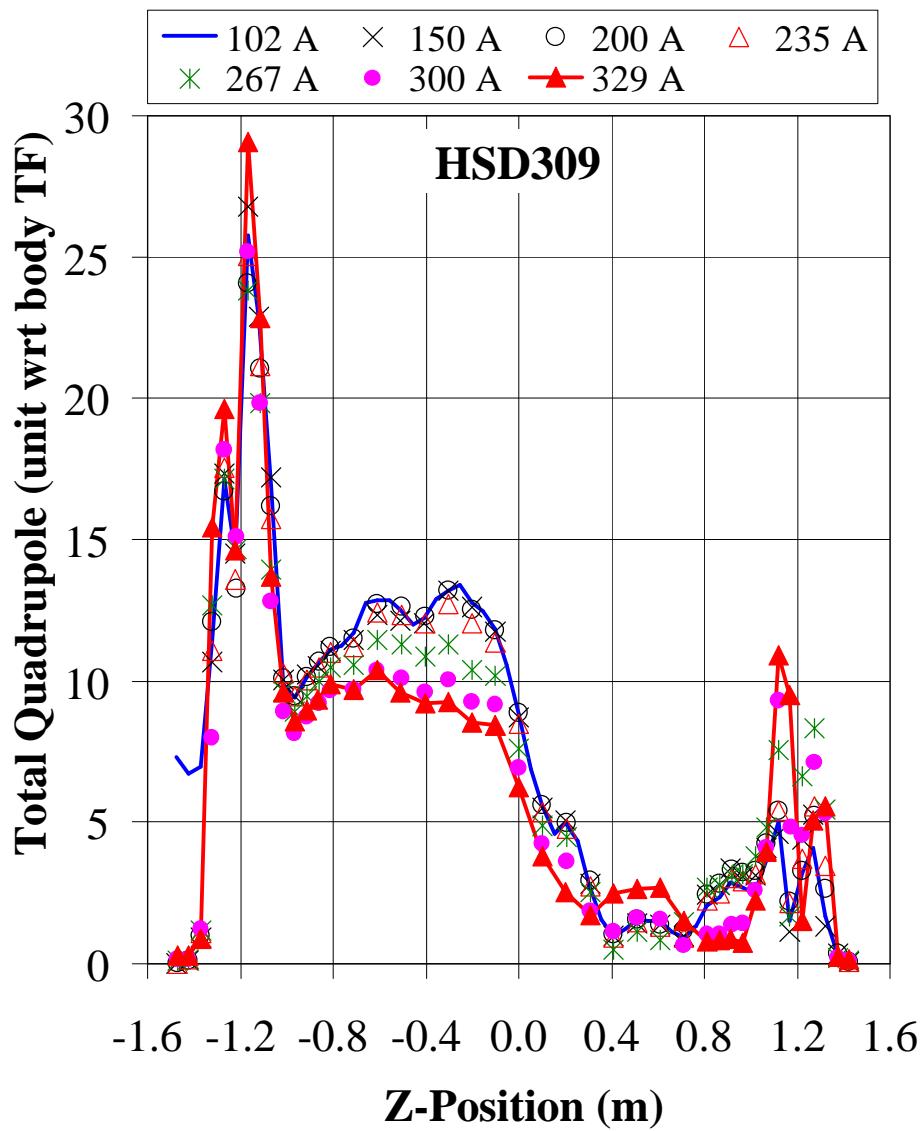
HSD Dipoles: Center; Shifted Data



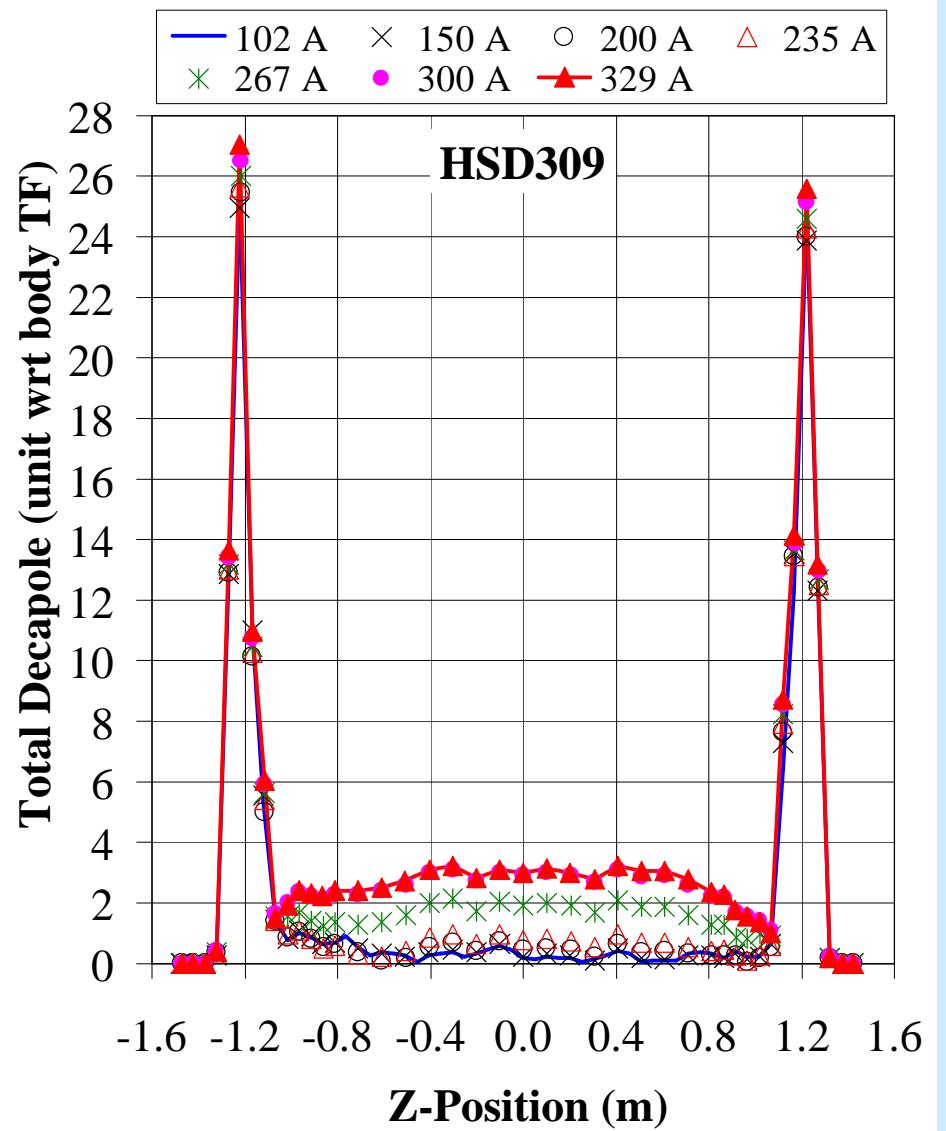
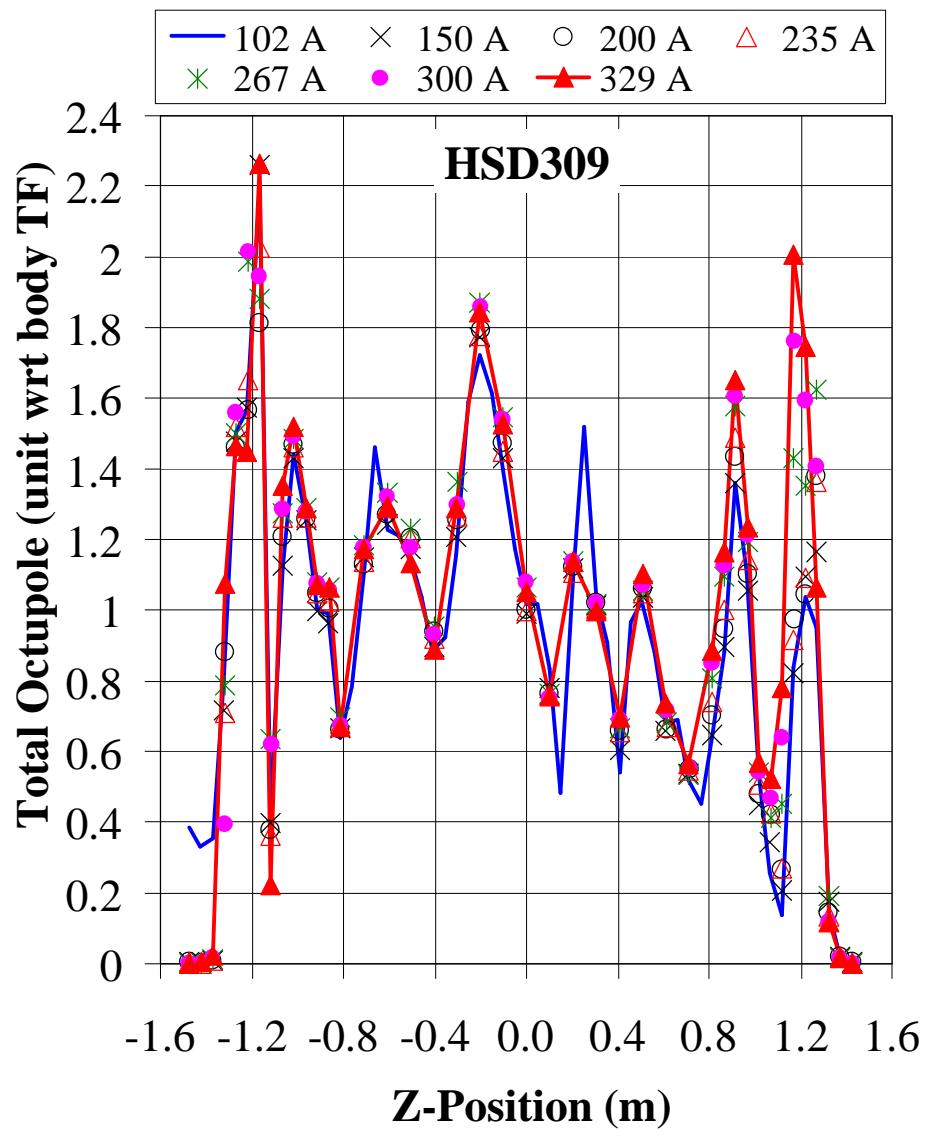
Z-Scan Data



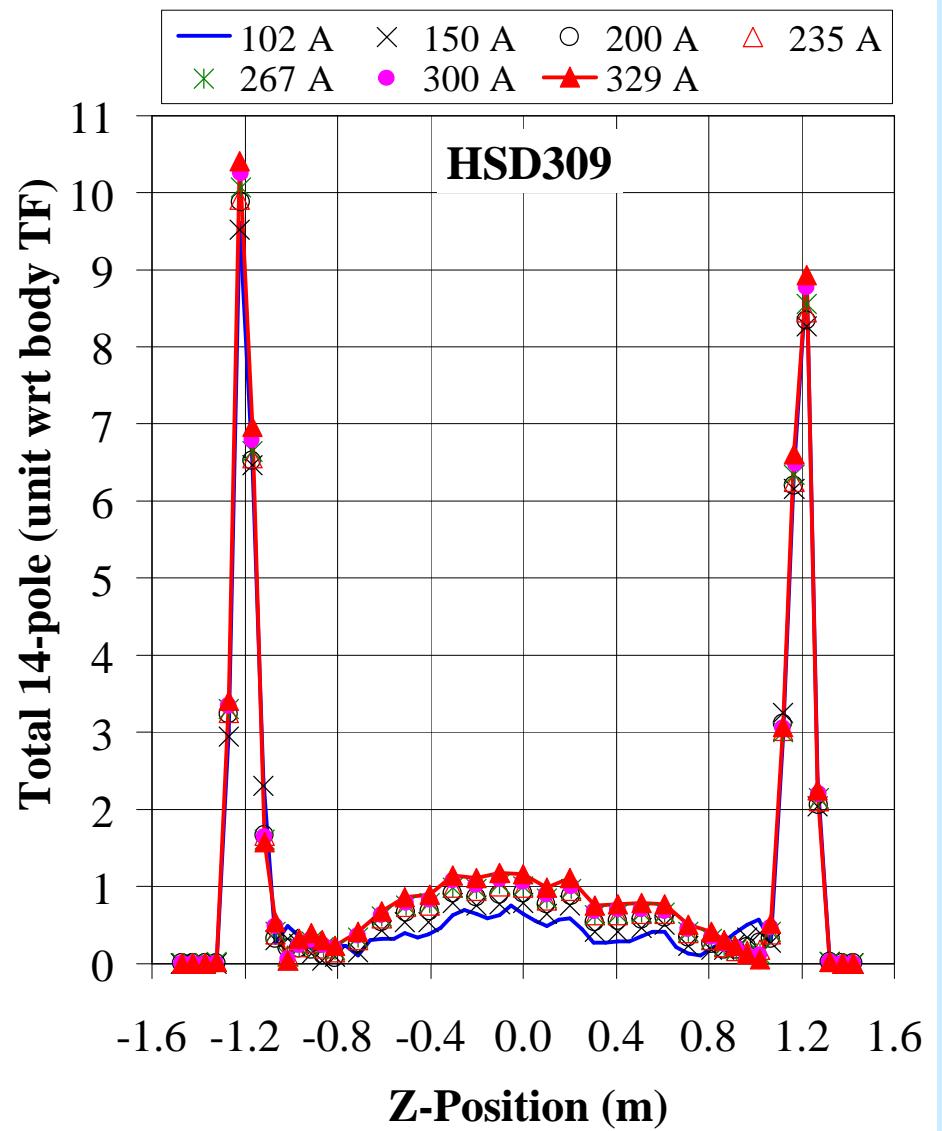
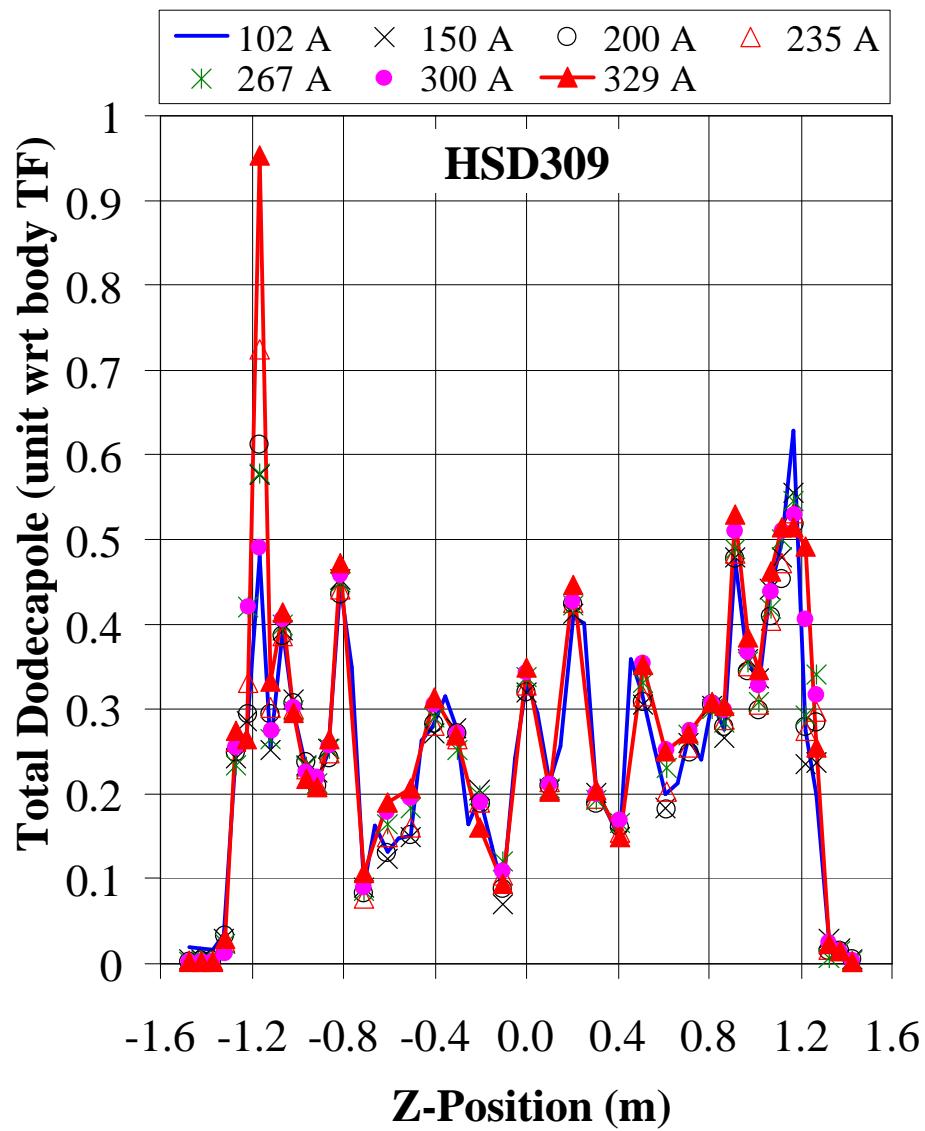
Z-Scan Data



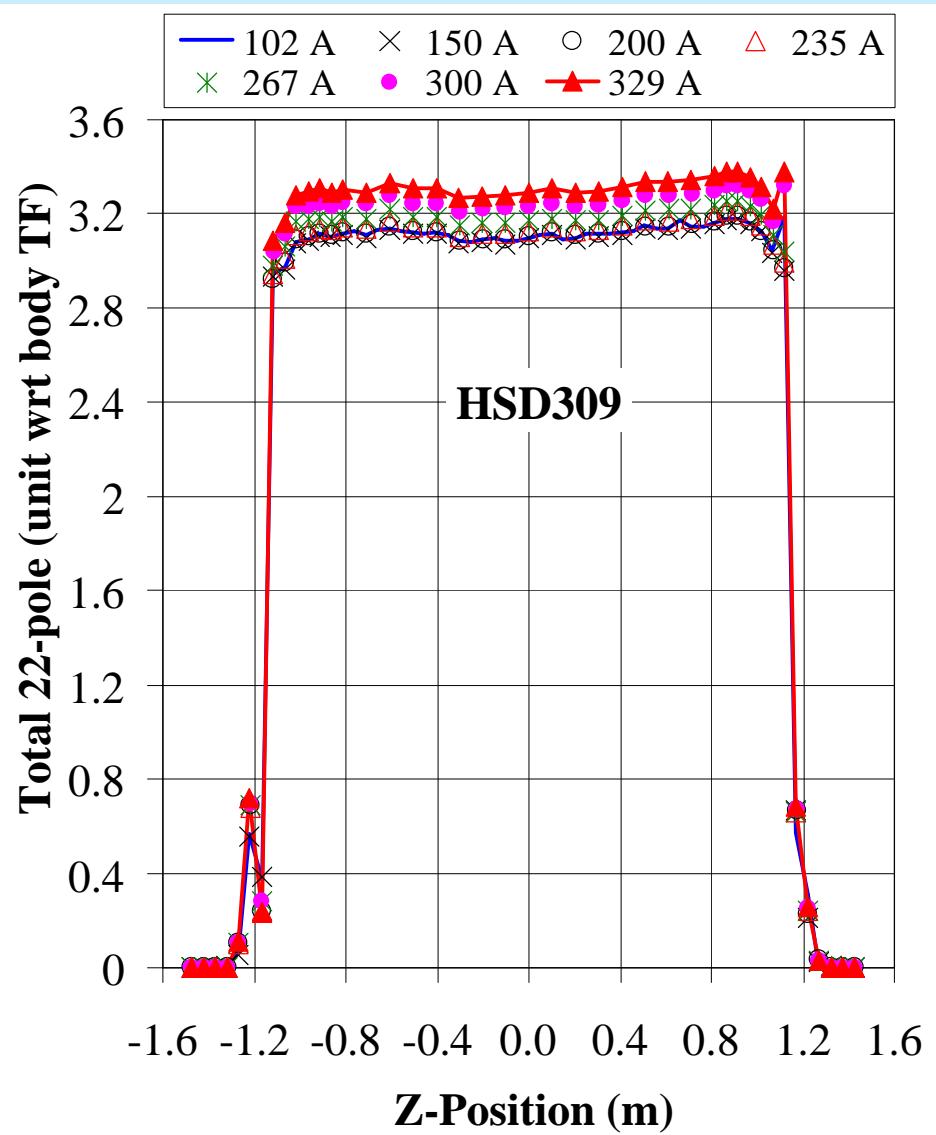
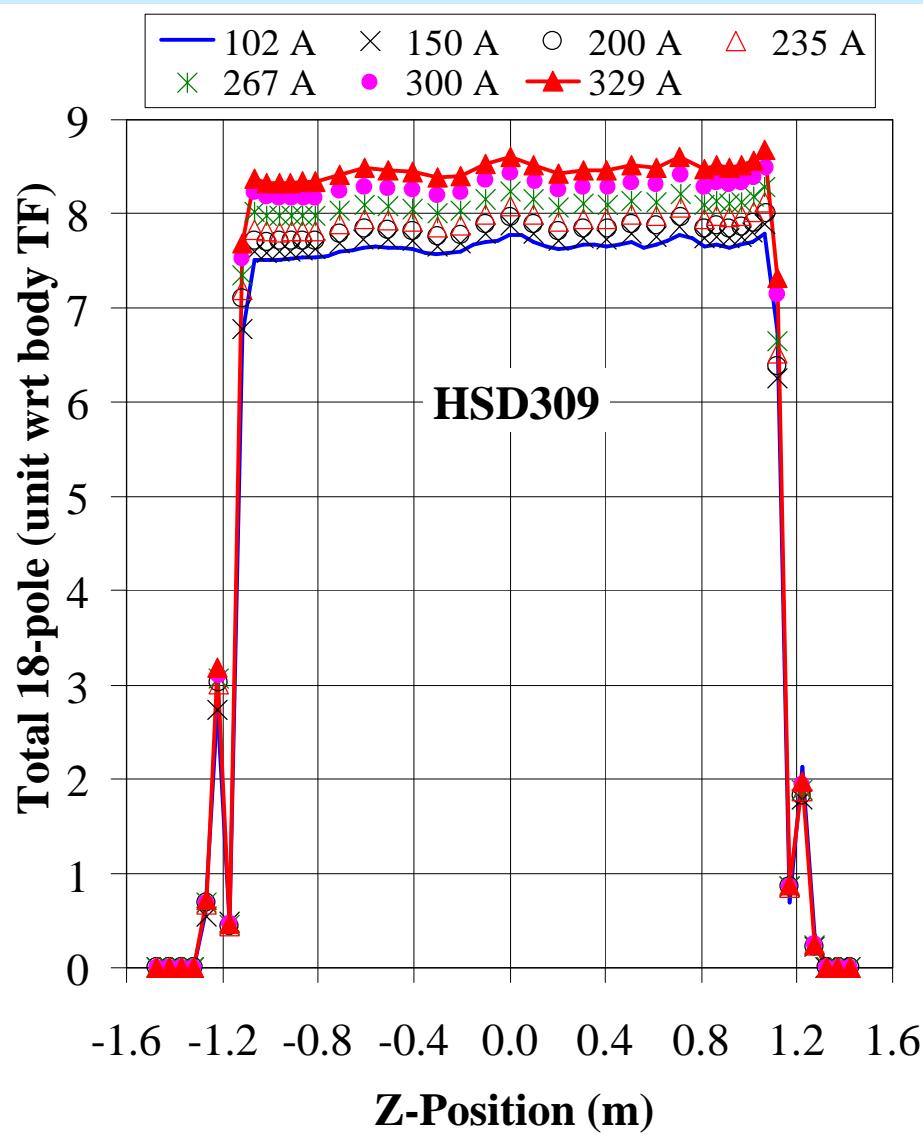
Z-Scan Data



Z-Scan Data



Z-Scan Data



Conclusions

- A measuring coil system for use in helical dipoles is presented.
- The short length of the coil (51 mm) allows precise measurements of the higher order terms by avoiding any significant cancellation of harmonics.
- Current dependence of harmonics is shown to have small magnet to magnet variations.
- Z-scans in small axial increments shows significant axial variation in the lower order harmonics.
- Analysis of the end regions has scope for further improvements.